

## Common Ions

Summary statistics for selected common ions, including dissolved solids, calcium, magnesium, sodium, percent sodium, sodium-adsorption ratio (SAR), potassium, bicarbonate, carbonate, sulfate, chloride, fluoride, bromide, iodide, and silica, are presented in table 4. The significance of the various common ions is described in table 1. Boxplots are presented in figure 16 for each of the common ions, except for carbonate. The water type for the various aquifers also is discussed in this section. Trilinear diagrams (fig. 17) are presented for each of the aquifers. Changes in water type as ground water flows down-gradient are discussed for the Madison, Minnelusa, and Inyan Kara aquifers.

Specific conductance can be used to estimate the concentration of dissolved solids using the equations presented in table 5. Linear regression was performed using specific conductance and concentrations of dissolved solids (sum of constituents or residue) for each aquifer having sufficient measurements of both to indicate the strength of the relation between specific conductance and dissolved solids concentration.

The general suitability of water for irrigation from the aquifers in the study area can be determined by using the South Dakota irrigation-water diagram (fig. 18). The diagram is based on South Dakota irrigation-water standards (revised January 7, 1982) and shows the State's water-quality and soil-texture requirements for the issuance of an irrigation permit. For each aquifer, the adjusted SAR, which is used to classify South Dakota irrigation waters, was calculated according to Koch (1983) from the mean concentrations of calcium, magnesium, sodium, and bicarbonate (or alkalinity from table 3) presented in table 4 for each aquifer. Based on mean concentrations, water from all aquifers, with the exceptions of the Pierre and Sundance aquifers, generally is suitable for irrigation, but may not be in specific instances if either the specific conductance or the SAR is high.

A strong relation exists between specific conductance and dissolved sulfate concentrations for samples from the Madison, Minnelusa, and Inyan Kara aquifers (fig. 19). Linear regression was performed using specific conductance and sulfate concentrations for each of these aquifers. Sulfate concentrations for these aquifers can be estimated using the equations presented in figure 19.

## Precambrian Aquifers

Generally, water from the Precambrian aquifers is fresh (less than 1,000 mg/L dissolved solids concentration). Calcium and bicarbonate generally are dominant among the common ions. Water from the Precambrian aquifers has the highest median chloride concentration, lowest mean and median concentrations of calcium, magnesium, and bicarbonate, and the lowest median sulfate (equal to the Deadwood aquifer) of the major aquifers.

The water type of the Precambrian aquifers generally is a calcium bicarbonate or a calcium magnesium bicarbonate type but also can be a mixed type (fig. 17). The original rock mineralogy, degree of metamorphism, and degree of weathering all can contribute to the variations in water type.

Two of 56 samples from Precambrian aquifers exceed the SMCL of 500 mg/L for dissolved solids. Two of 112 samples exceed the SMCL of 250 mg/L for sulfate; both were collected from the same well. Three of 55 samples exceed the SMCL of 2.0 mg/L for fluoride; all three samples were collected from the same well. None of the samples exceeded the MCL of 4.0 mg/L for fluoride.

### Deadwood Aquifer

Water from the Deadwood aquifer generally is fresh. Generally, calcium and bicarbonate are dominant among the common ions. Of samples collected from the major aquifers, the Deadwood aquifer has the lowest mean and median sulfate concentration (equal to the Precambrian aquifers). Variability in sulfate concentrations in the Deadwood aquifer is low.

The Deadwood aquifer generally has a calcium magnesium bicarbonate water type (fig. 17) in wells located on or near the outcrop. This water type results from the dissolution of calcite and dolomite. The downgradient water type is not known because no samples were collected from wells located more than 5 miles from the outcrop of the Deadwood Formation. Samples collected from three wells located about 3 miles from the outcrop have either a sodium bicarbonate or calcium sodium bicarbonate water type. Sodium may become the dominant cation in the Deadwood aquifer as the water flows downgradient.

Relations between various common ions and well depth are shown in figure 20. Fluoride and sodium concentrations, percent sodium, and SAR generally increase with increasing well depth. Two of 33 samples equal or exceed the MCL for fluoride; both of these samples were collected from a well with a depth of 1,105 feet.

**Table 4.** Summary of concentrations of common ions in ground water

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter except as indicated. One milligram per liter (mg/L) is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Precambrian aquifers</b>						
Solids, residue at 180°C	58	0	293	249	60	1,970
Solids, sum of constituents	56	0	230	221	54	642
Calcium	112	0	44	44	6.0	108
Magnesium	112	0	15	14	1.7	52
Sodium	108	0	10	8.1	1.5	70
Sodium, percent	57	0	13	10	6.0	41
Sodium-adsorption ratio	108	0	0.3	0.3	0	2.0
Potassium	58	0	4.0	3.8	1.0	16
Bicarbonate	22	0	165	168	21	268
Carbonate	0	0	--	--	--	--
Sulfate	112	9	35	21	<5.0	345
Chloride	109	41	11	5.6	0.5	161
Fluoride	55	3	0.5	0.3	0.1	2.5
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	64	0	10	8.6	3.5	27
<b>Deadwood aquifer</b>						
Solids, residue at 180°C	31	0	254	248	65	528
Solids, sum of constituents	32	0	262	248	48	469
Calcium	37	0	46	50	8.6	70
Magnesium	37	0	23	20	2.5	78
Sodium	37	0	17	5.9	1.2	160
Sodium, percent	32	0	14	7.0	1.0	85
Sodium-adsorption ratio	37	0	0.7	0.2	0	9.0
Potassium	32	0	2.8	2.2	0.1	10
Bicarbonate	3	0	249	260	220	268
Carbonate	2	0	0	0	0	0
Sulfate	37	2	27	21	3.4	88
Chloride	37	4	5.2	2.0	0.5	40
Fluoride	33	1	0.7	0.3	<0.1	5.4
Bromide	1	0	--	--	0.3	0.3
Iodide	0	0	--	--	--	--
Silica	33	0	11	10	3.3	18
<b>Madison aquifer</b>						
Solids, residue at 180°C	80	0	490	260	162	2,300
Solids, sum of constituents	99	0	428	260	161	1,820
Calcium	127	0	70	54	5.6	430
Magnesium	127	0	26	25	2.0	120
Sodium	122	0	39	5.4	0.8	260
Sodium, percent	103	0	14	6.0	1.0	57
Sodium-adsorption ratio	122	0	1.0	0.2	0	18
Potassium	103	0	6.0	2.8	0.7	55
Bicarbonate	41	0	250	222	166	454
Carbonate	24	0	0.3	0	0	6.0

**Table 4.** Summary of concentrations of common ions in ground water—Continued

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter except as indicated. One milligram per liter (mg/L) is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Madison aquifer—Continued</b>						
Sulfate	127	10	96	23	<1.0	453
Chloride	124	15	55	3.5	0.2	1,000
Fluoride	89	0	0.7	0.4	0.1	18
Bromide	4	0	0.18	0.10	0.1	0.4
Iodide	2	0	0.03	0.03	0.01	0.04
Silica	62	0	11	11	3.4	34
<b>Minnelusa aquifer</b>						
Solids, residue at 180°C	190	0	619	296	128	5,055
Solids, sum of constituents	176	0	512	271	120	2,700
Calcium	250	0	127	68	2.2	695
Magnesium	248	0	32	23	0.6	194
Sodium	245	0	18	3.8	0.05	731
Sodium, percent	196	0	4.4	2.0	0	37
Sodium-adsorption ratio	243	0	0.3	0.1	0	21
Potassium	197	0	3.0	2.0	0.7	19
Bicarbonate	86	0	252	249	149	370
Carbonate	15	0	--	0	0	10
Sulfate	249	15	257	32	<2.0	3,438
Chloride	236	38	12	2.0	<0.1	230
Fluoride	185	8	0.5	0.3	0.01	2.8
Bromide	5	0	0.3	0.1	0.1	0.8
Iodide	3	0	0.01	0.01	0.01	0.01
Silica	104	0	9.8	11	2.2	33
<b>Minnekahta aquifer</b>						
Solids, residue at 180°C	24	0	509	346	228	2,255
Solids, sum of constituents	24	0	410	330	233	1,920
Calcium	28	0	109	80	45	425
Magnesium	28	0	30	26	12	105
Sodium	26	0	7.9	4.0	1.1	100
Sodium, percent	25	0	3.2	2.0	1.0	15
Sodium-adsorption ratio	26	0	0.1	0.1	0	1.0
Potassium	25	0	2.4	1.9	1.1	12
Bicarbonate	21	0	321	316	230	412
Carbonate	2	0	0	0	0	0
Sulfate	28	1	139	32	<1.0	1,385
Chloride	28	2	7.5	3.0	0.5	119
Fluoride	25	4	0.3	0.2	<0.1	1.0
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	7	0	12	12	4.8	24
<b>Inyan Kara aquifer</b>						
Solids, residue at 180°C	111	0	760	682	174	3,170
Solids, sum of constituents	102	0	742	673	170	3,300
Calcium	177	0	95	71	1.6	505

**Table 4.** Summary of concentrations of common ions in ground water—Continued

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter except as indicated. One milligram per liter (mg/L) is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Inyan Kara aquifer—Continued</b>						
Magnesium	174	1	34	24	<1.0	279
Sodium	171	0	145	127	1.0	1,000
Sodium, percent	103	0	45	37	1.0	99
Sodium-adsorption ratio	169	0	8.9	2.0	0	79
Potassium	105	0	6.4	6.2	0.1	19
Bicarbonate	31	0	254	258	167	438
Carbonate	0	0	--	--	--	--
Sulfate	177	0	462	330	5.0	2,030
Chloride	176	42	11	5.0	0.1	140
Fluoride	105	1	0.6	0.5	0.1	4.0
Bromide	9	0	0.2	0.1	0.1	0.7
Iodide	10	0	0.04	0.01	0.01	0.26
Silica	112	1	6.1	4.6	<0.1	17
<b>Spearfish aquifer</b>						
Solids, residue at 180°C	3	0	294	286	274	322
Solids, sum of constituents	3	0	257	259	247	266
Calcium	13	0	223	116	36	661
Magnesium	13	0	42	23	10	109
Sodium	13	0	63	5.0	2.0	608
Sodium, percent	4	0	3.3	2.0	2.0	7.0
Sodium-adsorption ratio	13	0	0.9	0.2	0.1	8.0
Potassium	4	0	3.9	2.1	1.5	10
Bicarbonate	2	0	224	224	221	227
Carbonate	0	0	--	--	--	--
Sulfate	13	0	635	98	10	2,338
Chloride	13	7	11	4.4	1.5	50
Fluoride	4	0	0.6	0.3	0.2	1.6
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	9	0	5.5	4.8	3.5	9.4
<b>Sundance aquifer</b>						
Solids, residue at 180°C	12	0	1,264	1,440	414	1,930
Solids, sum of constituents	12	0	1,202	1,365	399	1,820
Calcium	14	0	155	150	56	352
Magnesium	14	0	86	89	10	220
Sodium	14	0	144	118	6.7	512
Sodium, percent	12	0	29	24	3.0	84
Sodium-adsorption ratio	14	0	3.3	2.0	0.2	16
Potassium	12	0	8.2	6.9	3.9	14
Bicarbonate	2	0	305	305	283	326
Carbonate	0	0	--	--	--	--
Sulfate	14	0	780	1,000	99	1,724
Chloride	14	0	13	8.2	1.1	65
Fluoride	12	0	2.5	0.5	0.1	25

**Table 4.** Summary of concentrations of common ions in ground water—Continued

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter except as indicated. One milligram per liter (mg/L) is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Sundance aquifer—Continued</b>						
Bromide	2	0	0.15	0.15	0.1	0.2
Iodide	2	0	0.03	0.03	0.01	0.05
Silica	13	0	10	9.7	2.2	26
<b>Morrison aquifer</b>						
Solids, residue at 180°C	8	0	460	383	256	751
Solids, sum of constituents	7	0	443	340	234	793
Calcium	15	0	146	74	2.5	519
Magnesium	15	0	52	23	1.1	268
Sodium	13	0	77	30	2.7	357
Sodium, percent	8	0	22	15	5.0	81
Sodium-adsorption ratio	13	0	2.8	0.8	0	19
Potassium	8	0	6.4	6.7	2.9	9.0
Bicarbonate	1	0	--	--	208	208
Carbonate	0	0	--	--	--	--
Sulfate	15	0	489	208	46	2,056
Chloride	15	5	7.8	3.0	0.4	56
Fluoride	9	0	0.5	0.5	0.2	0.9
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	11	0	8.9	5.3	3.8	17
<b>Pierre aquifer</b>						
Solids, residue at 180°C	0	0	--	--	--	--
Solids, sum of constituents	0	0	--	--	--	--
Calcium	28	0	164	144	41	365
Magnesium	28	0	88	49	10	508
Sodium	28	0	227	176	8.7	757
Sodium, percent	0	0	--	--	--	--
Sodium-adsorption ratio	28	0	3.6	3.0	0.3	11
Potassium	0	0	--	--	--	--
Bicarbonate	0	0	--	--	--	--
Carbonate	0	0	--	--	--	--
Sulfate	28	0	964	659	15	4,126
Chloride	28	7	52	26	<10	222
Fluoride	0	0	--	--	--	--
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	28	0	6.9	6.3	2.0	13
<b>Graneros aquifer</b>						
Solids, residue at 180°C	0	0	---	--	--	--
Solids, sum of constituents	0	0	--	--	--	--
Calcium	10	0	168	133	25	459
Magnesium	10	0	54	51	12	122
Sodium	10	0	91	66	3.6	289
Sodium, percent	0	0	--	--	--	--

**Table 4.** Summary of concentrations of common ions in ground water—Continued

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Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Graneros aquifer—Continued</b>						
Sodium-adsorption ratio	10	0	1.6	1.5	0	4.0
Potassium	0	0	--	--	--	--
Bicarbonate	0	0	--	--	--	--
Carbonate	0	0	--	--	--	--
Sulfate	10	0	539	286	87	1,598
Chloride	10	7	41	39	<10	57
Fluoride	0	0				
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	10	0	4.7	4.7	3.7	6.4
<b>Newcastle aquifer</b>						
Solids, residue at 180°C	8	0	460	400	279	1,010
Solids, sum of constituents	8	0	415	355	277	862
Calcium	8	0	80	76	10	170
Magnesium	8	0	18	18	1.9	32
Sodium	8	0	35	13	8.0	164
Sodium, percent	8	0	20	11	6.0	90
Sodium-adsorption ratio	8	0	1.9	0.4	0.2	12
Potassium	8	0	8.0	7.1	4.1	17
Bicarbonate	0	0	--	--	--	--
Carbonate	0	0	--	--	--	--
Sulfate	8	0	128	103	23	410
Chloride	8	0	3.4	2.6	1.1	8.7
Fluoride	8	0	0.6	0.6	0.3	1.4
Bromide	0	0	--	--	--	--
Iodide	0	0	--	--	--	--
Silica	5	0	8.4	8.6	6.9	10
<b>Alluvial aquifers</b>						
Solids, residue at 180°C	78	0	559	329	127	2,380
Solids, sum of constituents	81	0	503	323	100	2,280
Calcium	116	0	121	77	13	536
Magnesium	116	0	39	25	3.2	274
Sodium	115	0	62	10	2.0	778
Sodium, percent	85	0	13	6.0	1.0	87
Sodium-adsorption ratio	115	0	1.1	0.3	0	12
Potassium	85	0	5.0	4.0	0.9	42
Bicarbonate	21	0	266	244	158	458
Carbonate	3	0	0	0	0	0
Sulfate	116	0	360	99	2.9	3,000
Chloride	114	15	19	6.1	1.0	194
Fluoride	73	1	0.4	0.3	0.1	1.5
Bromide	3	0	0.09	0.08	0.06	0.13
Iodide	0	0	--	--	--	--
Silica	51	0	7.7	7.1	0.7	25

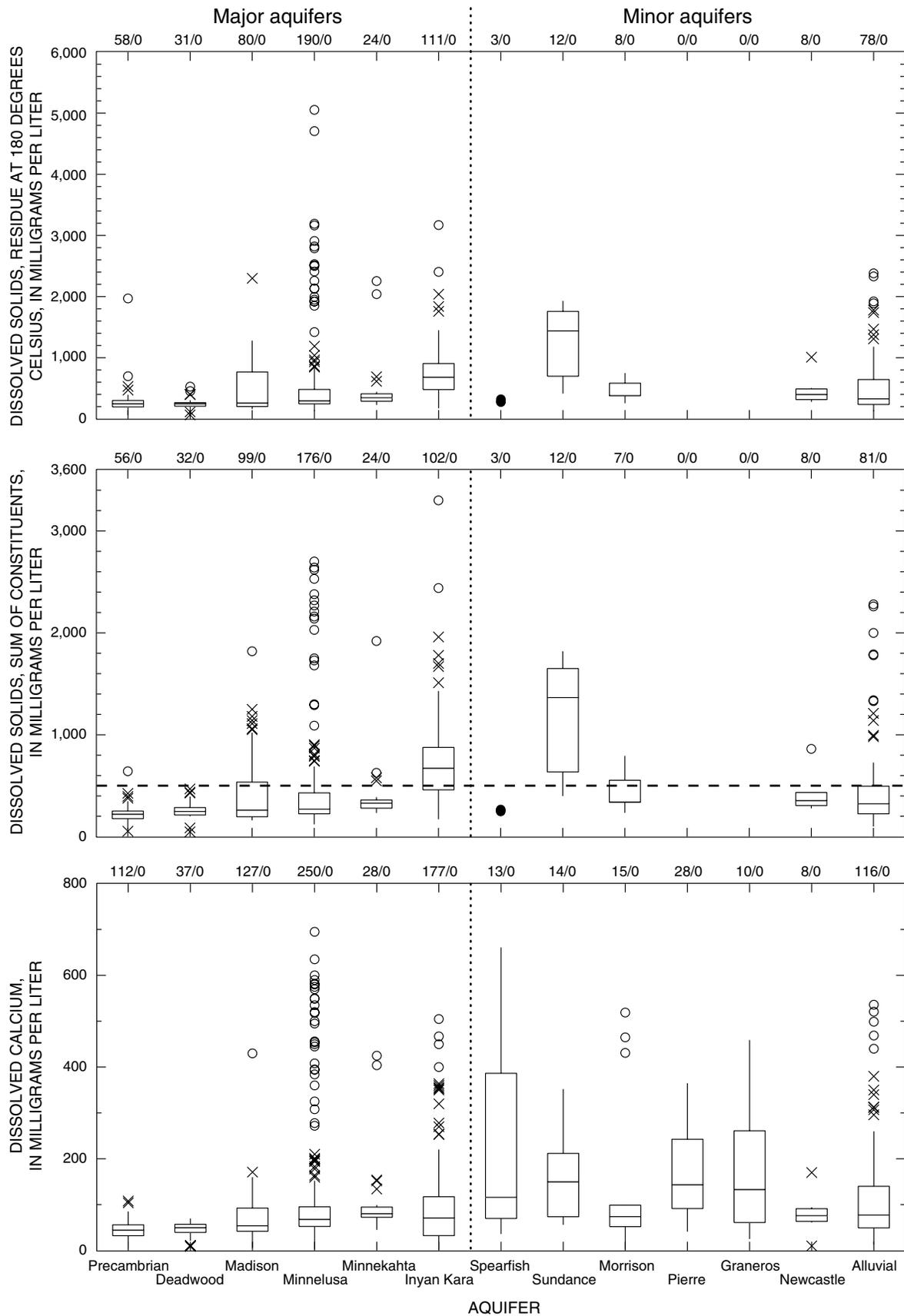


Figure 16. Boxplots of concentrations of selected common ions for selected aquifers.

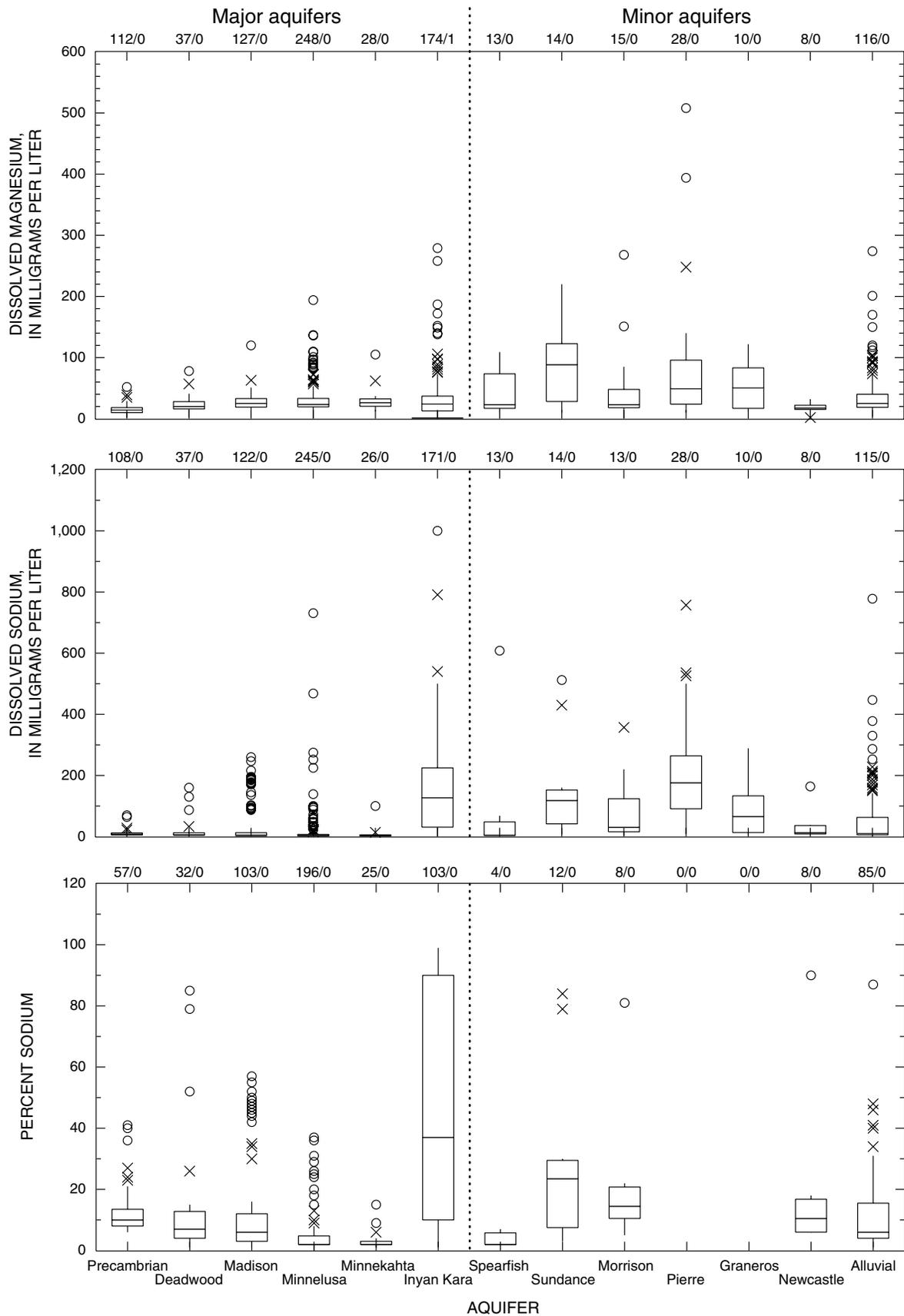


Figure 16. Boxplots of concentrations of selected common ions for selected aquifers.--Continued

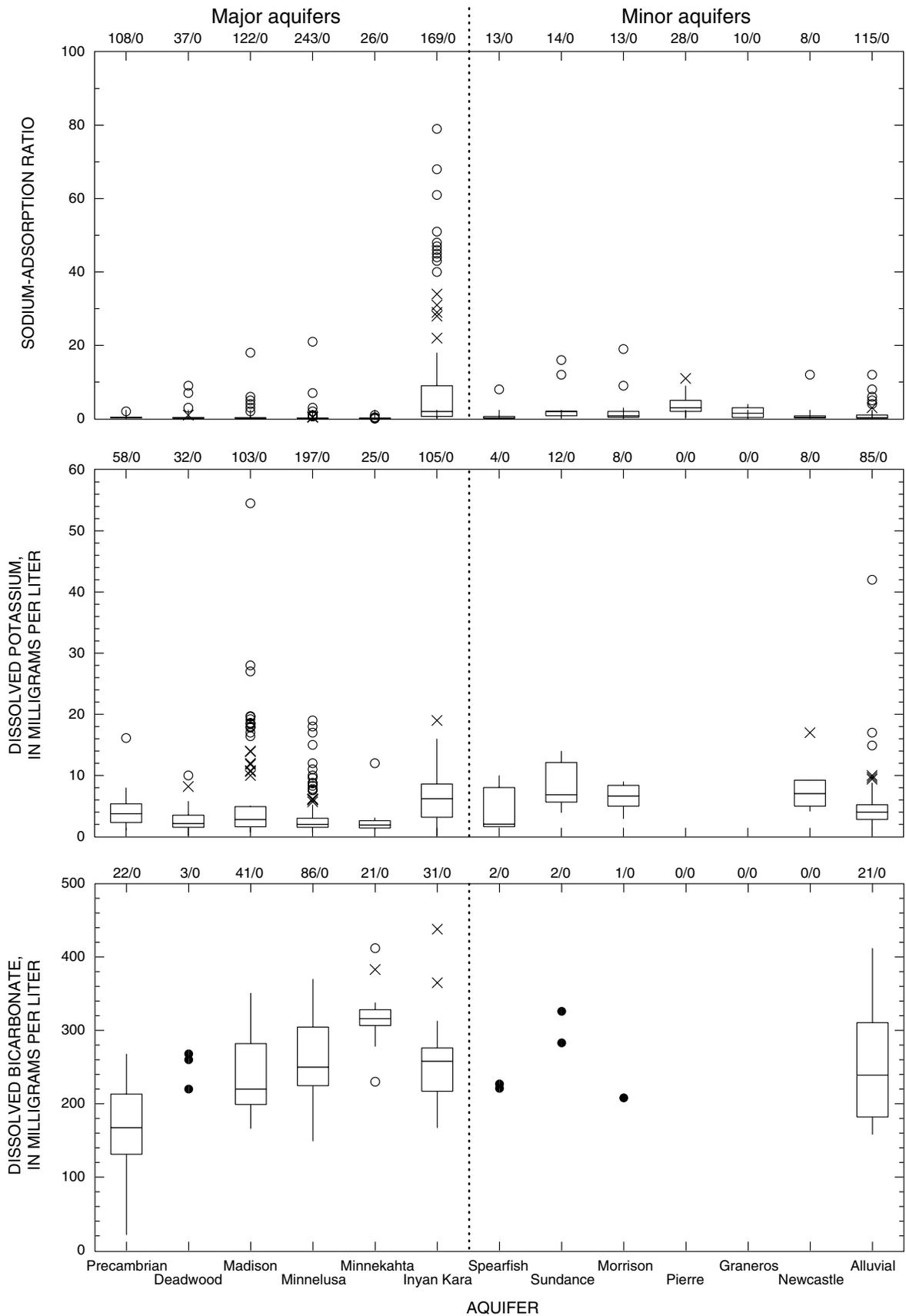


Figure 16. Boxplots of concentrations of selected common ions for selected aquifers.--Continued

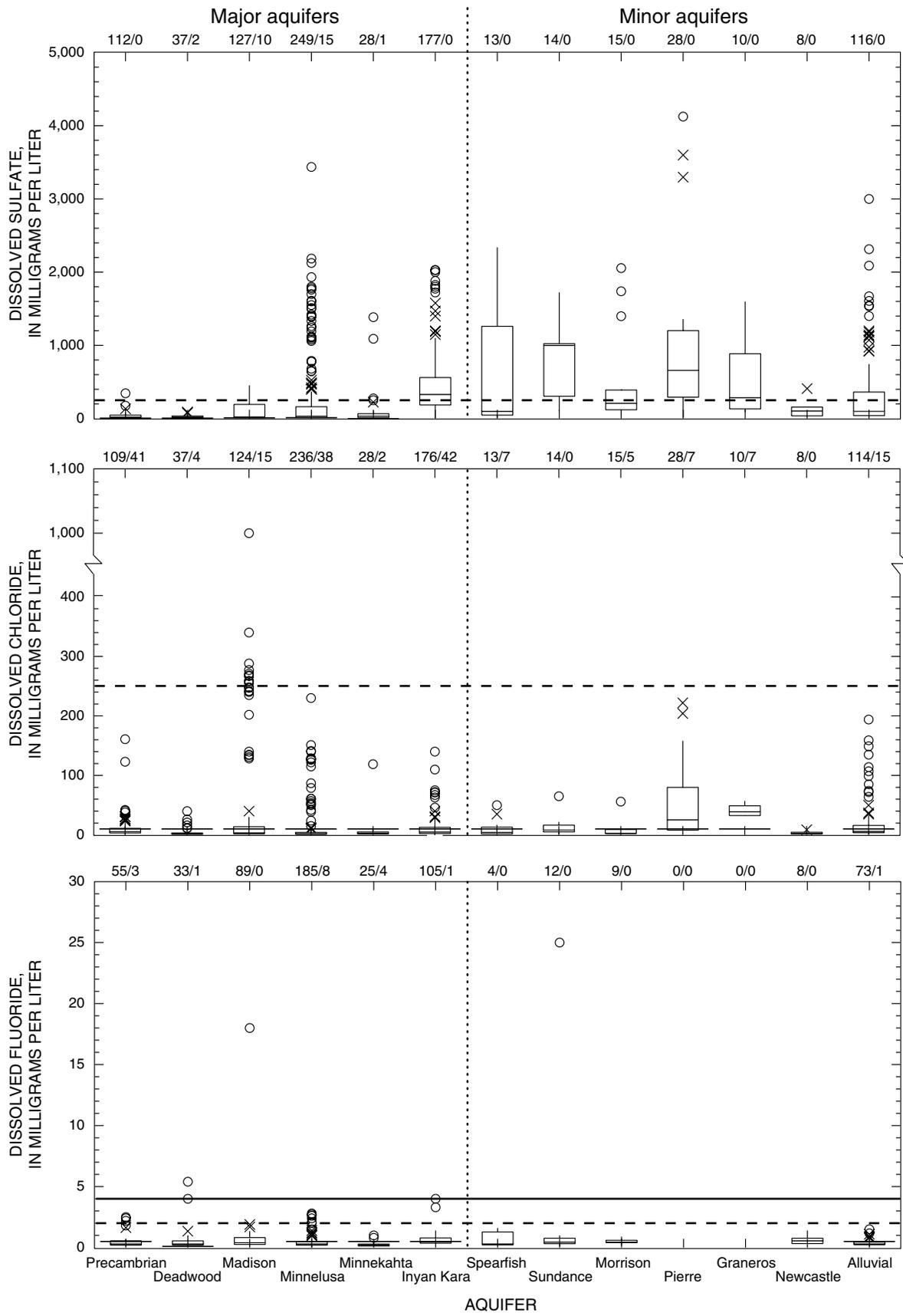


Figure 16. Boxplots of concentrations of selected common ions for selected aquifers.--Continued

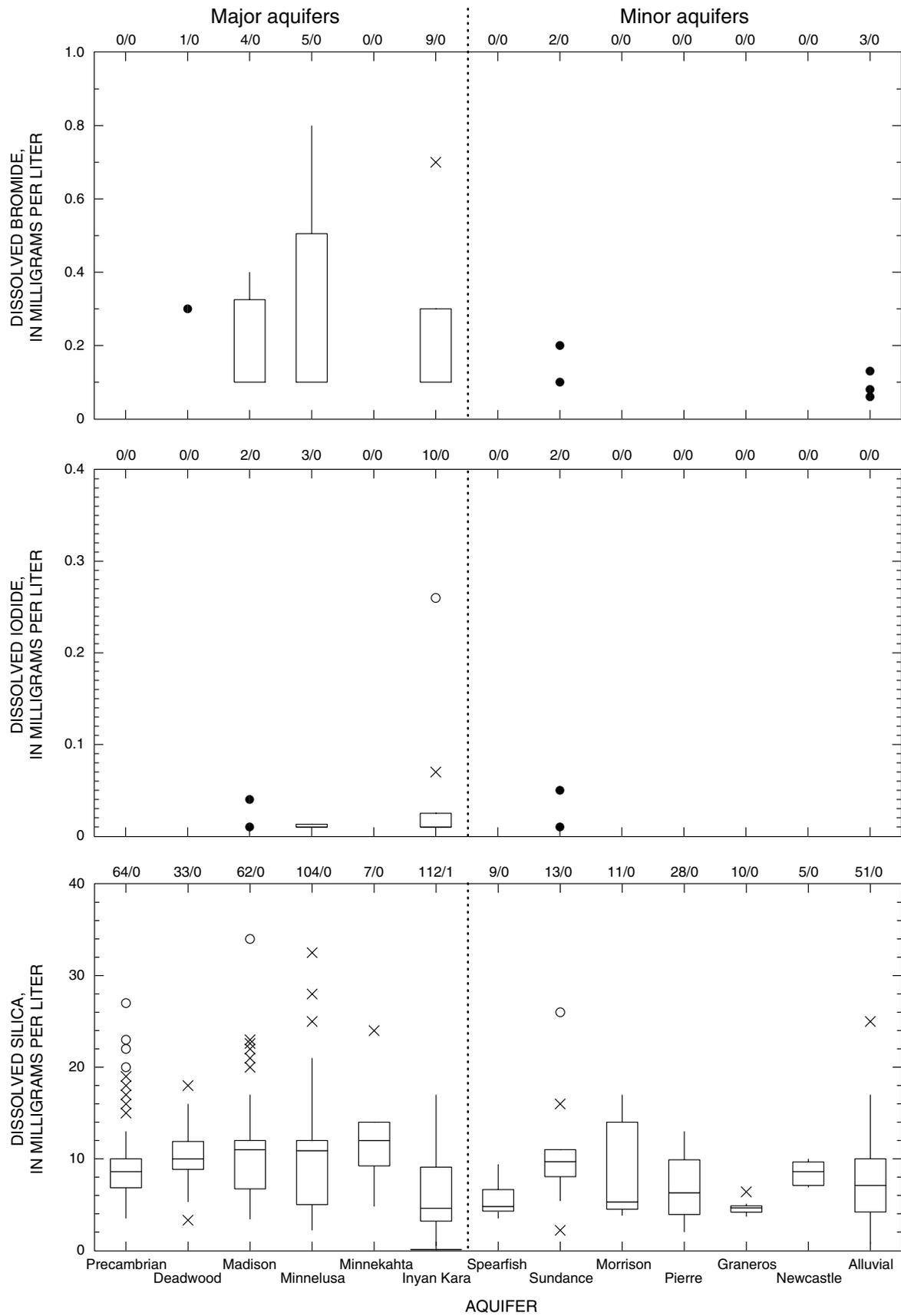
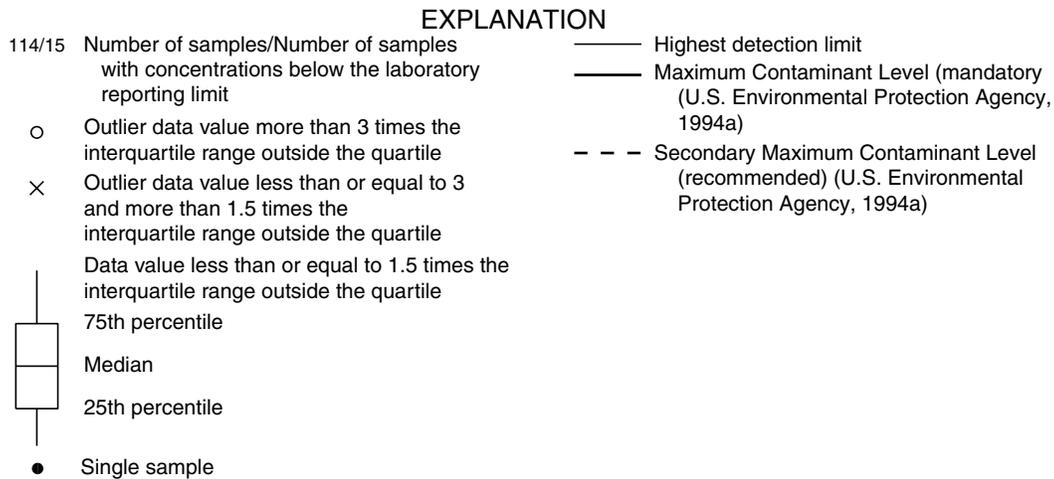


Figure 16. Boxplots of concentrations of selected common ions for selected aquifers.--Continued



**Figure 16.** Boxplots of concentrations of selected common ions for selected aquifers.--Continued

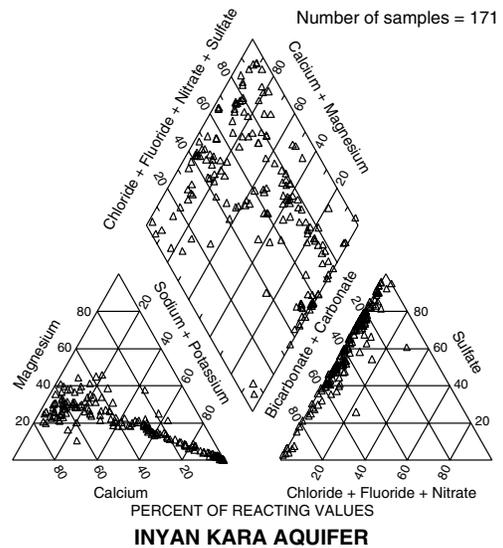
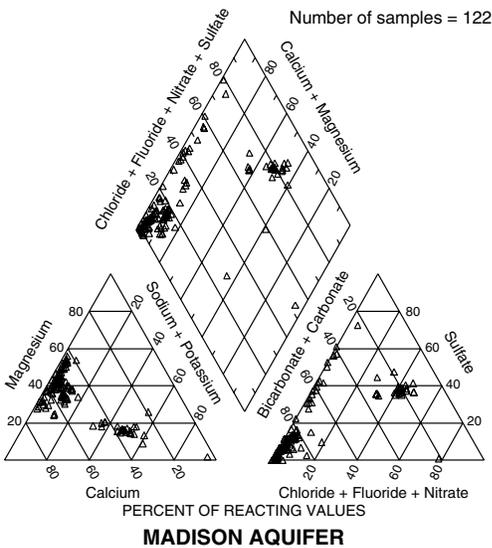
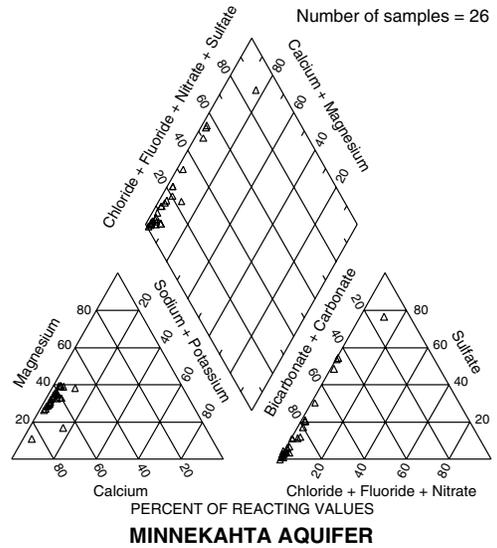
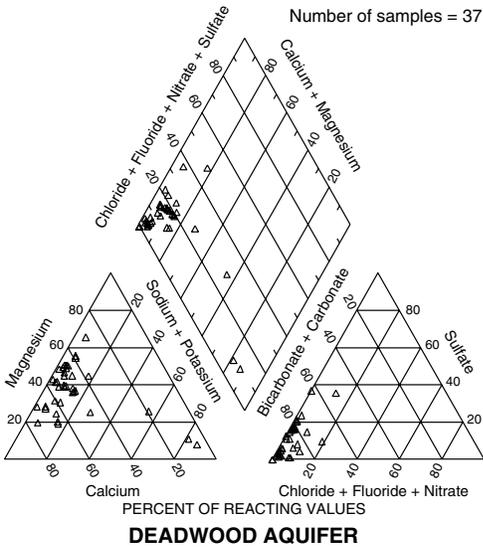
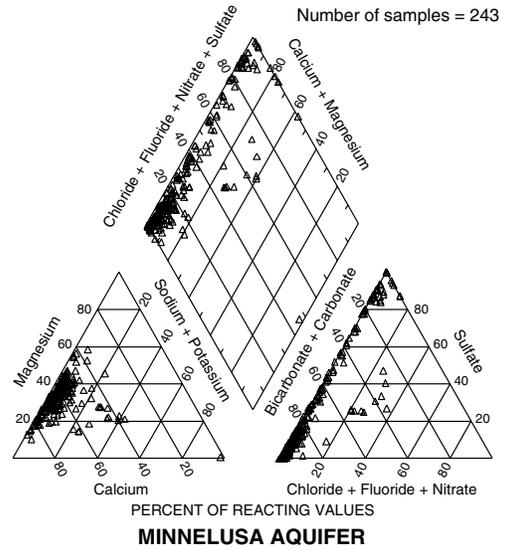
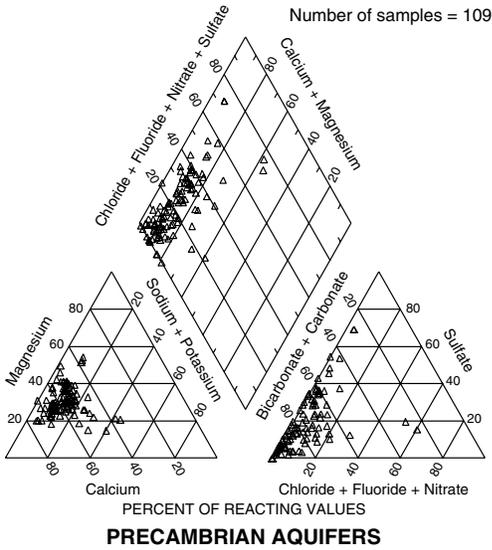


Figure 17. Trilinear diagrams showing proportional concentrations of major ions in selected aquifers.

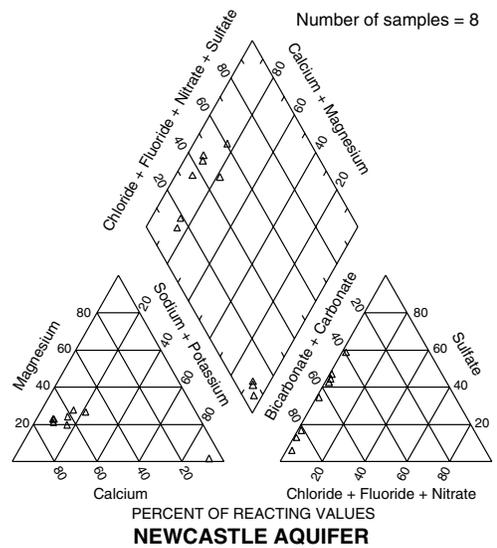
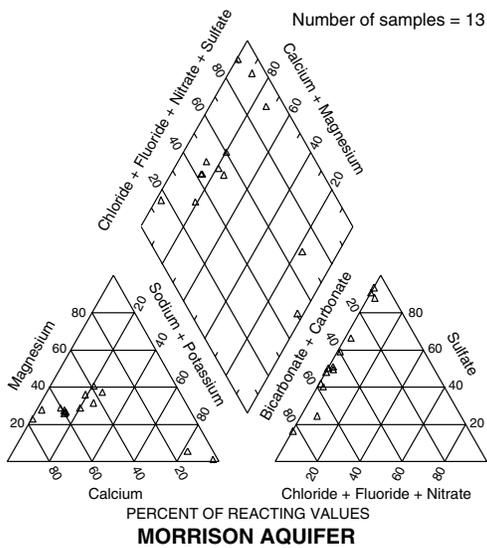
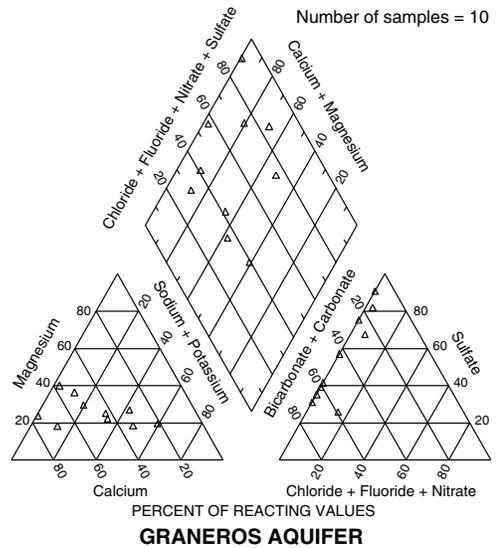
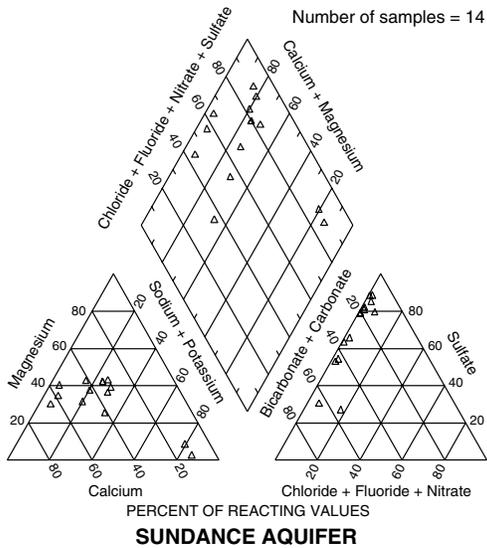
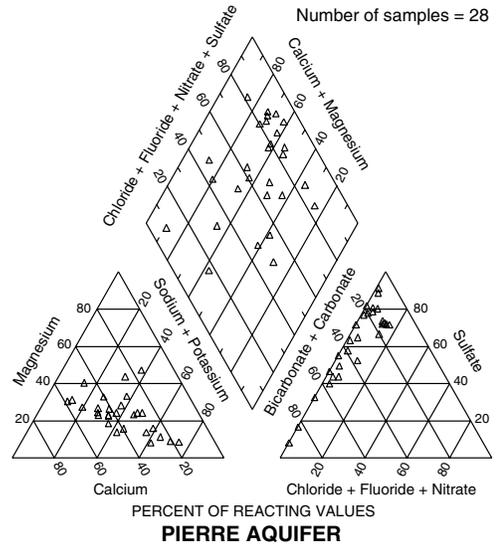
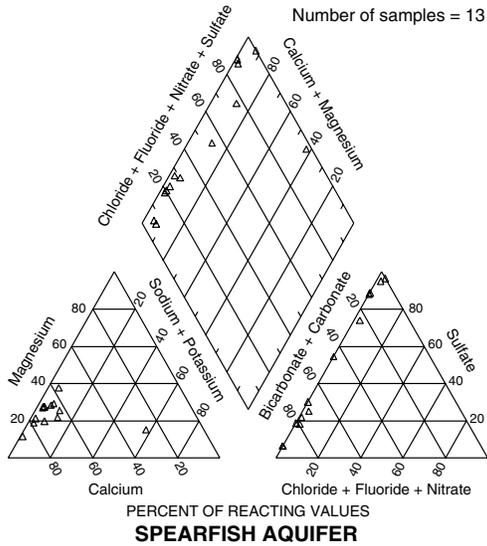
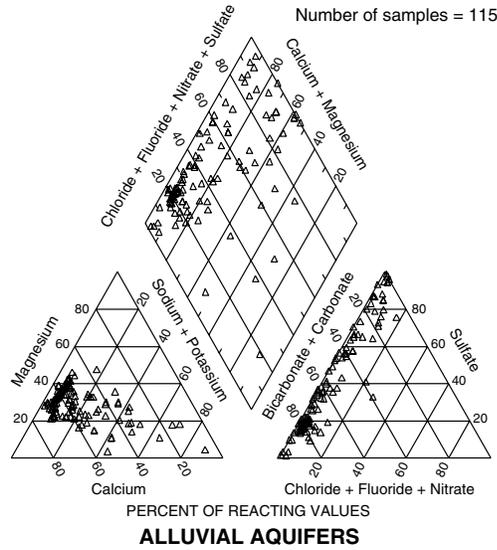


Figure 17. Trilinear diagrams showing proportional concentrations of major ions in selected aquifers.--Continued

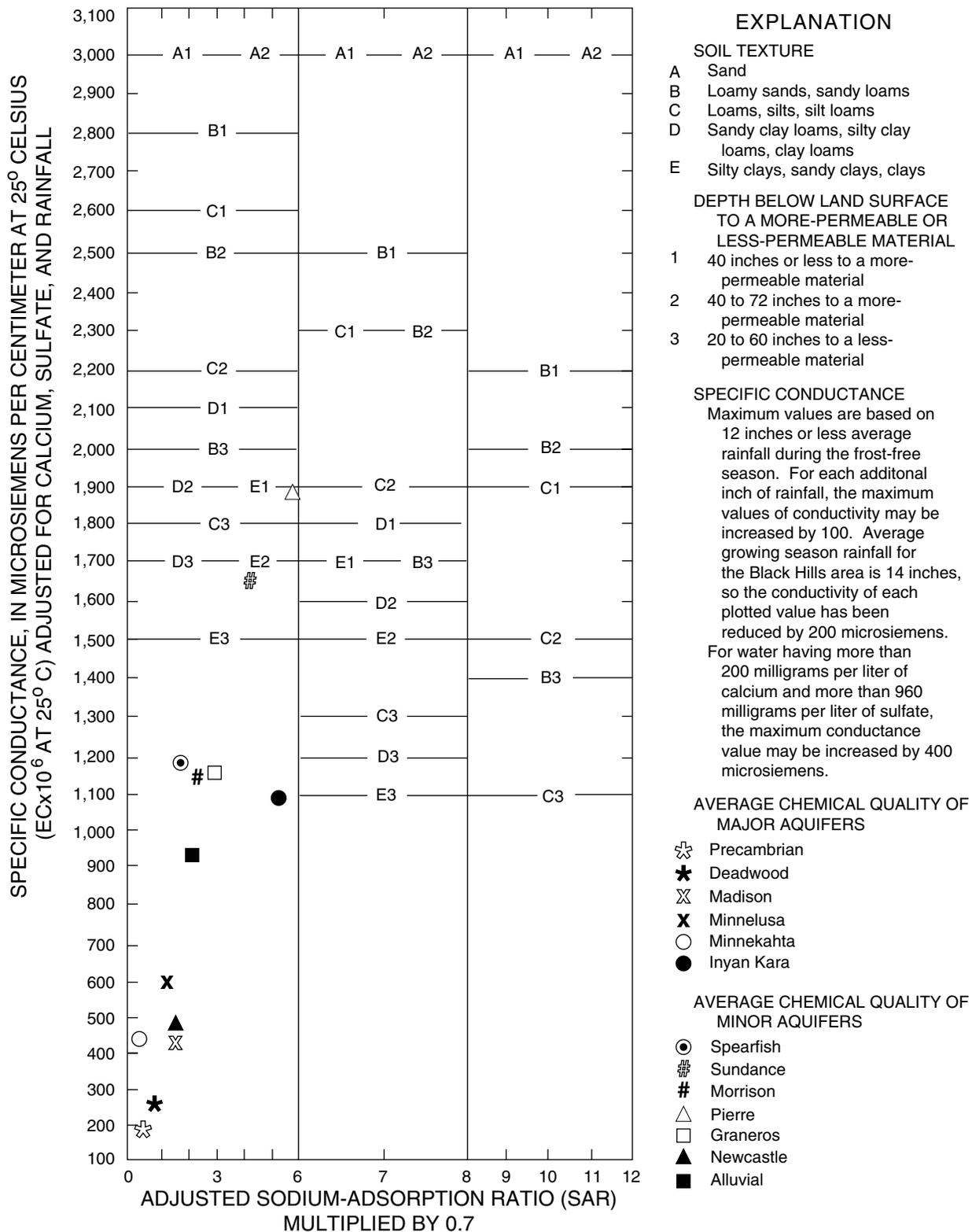


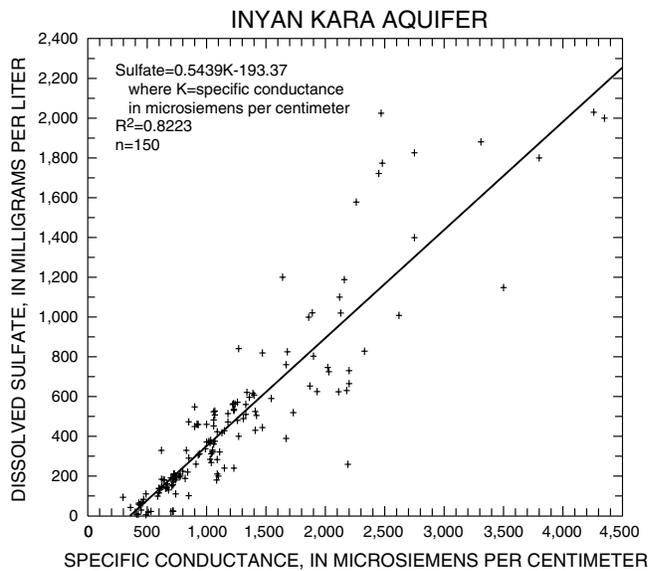
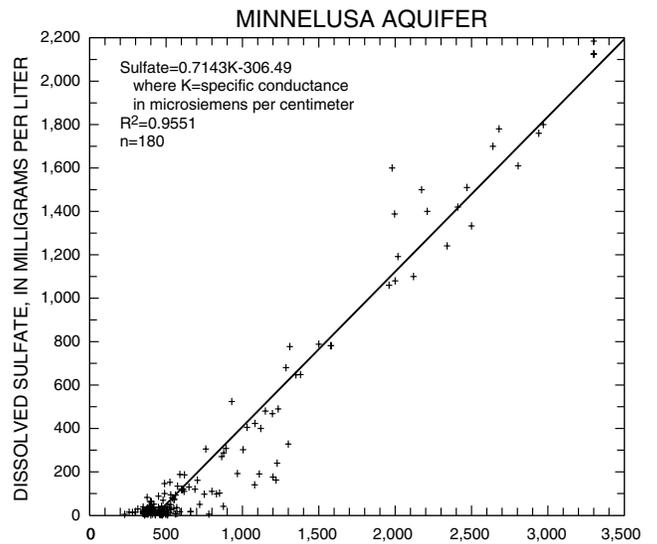
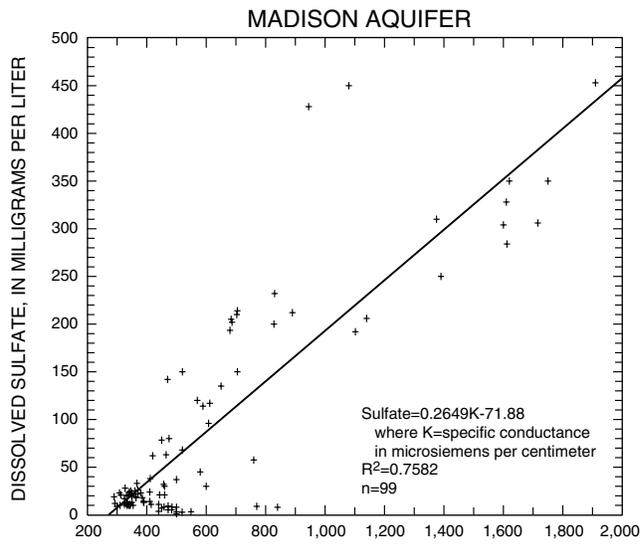
**Figure 17.** Trilinear diagrams showing proportional concentrations of major ions in selected aquifers.--Continued

**Table 5.** Relation between specific conductance and dissolved solids for selected aquifers

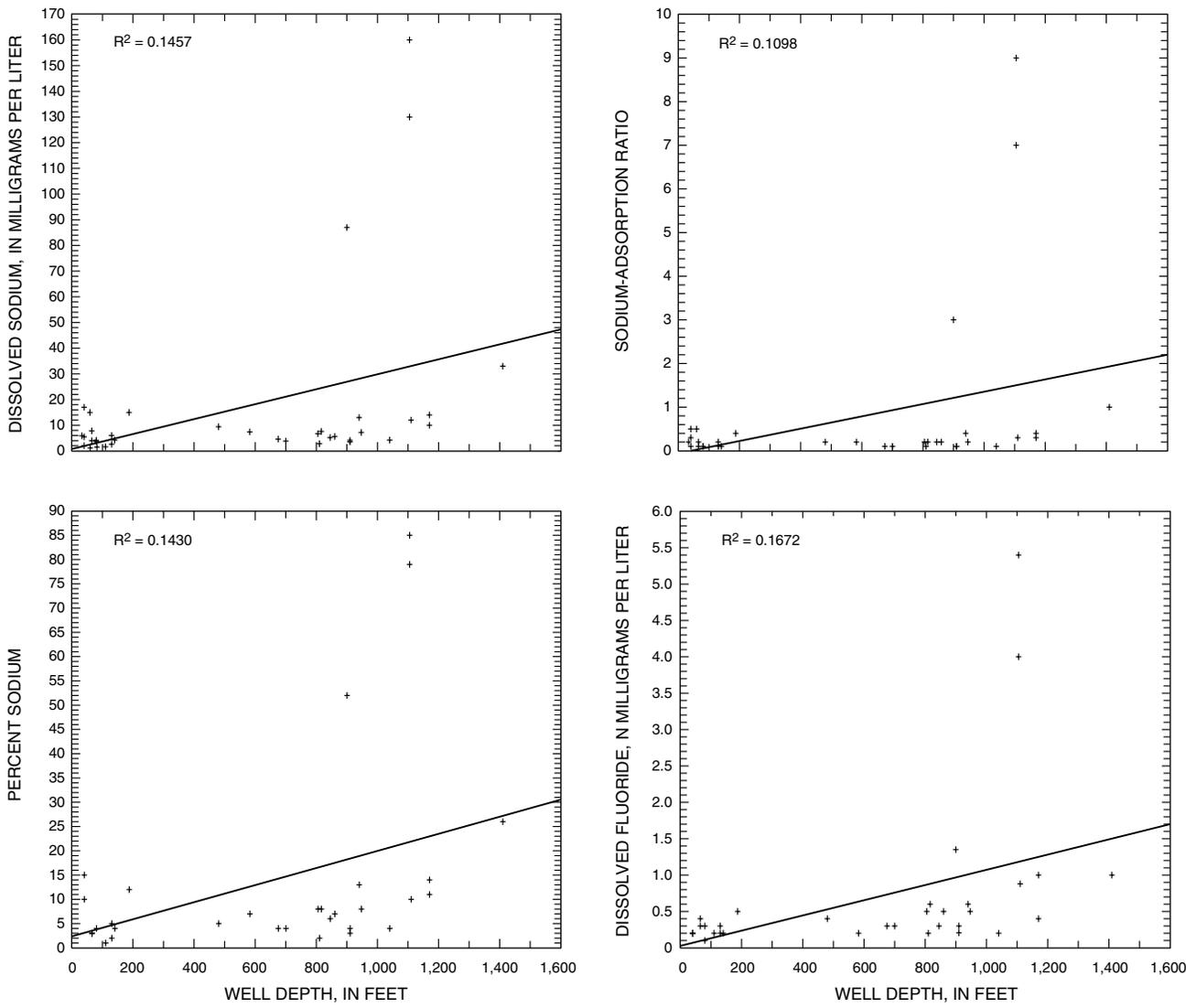
[*S* = dissolved solids, in milligrams per liter; *K* = specific conductance, in microsiemens per centimeter]

Aquifer	Equation of line	R <sup>2</sup>	Number of samples
Precambrian	$S = 0.6151K - 14.42$	0.9108	39
Deadwood	$S = 0.5792K - 1.93$	.9687	33
Madison	$S = 0.6091K - 3.73$	.9793	91
Minnelusa	$S = 1.0070K - 215.09$	.9777	159
Minnekahta	$S = 0.8860K - 177.62$	.9912	25
Inyan Kara	$S = 0.7842K - 98.49$	.9479	85
Sundance	$S = 0.7986K - 129.34$	.9750	10
Morrison	$S = 0.7601K - 66.71$	.9781	7
Newcastle	$S = 0.7105K - 67.20$	.9817	8
Alluvial	$S = 0.8302K - 105.62$	.9601	64



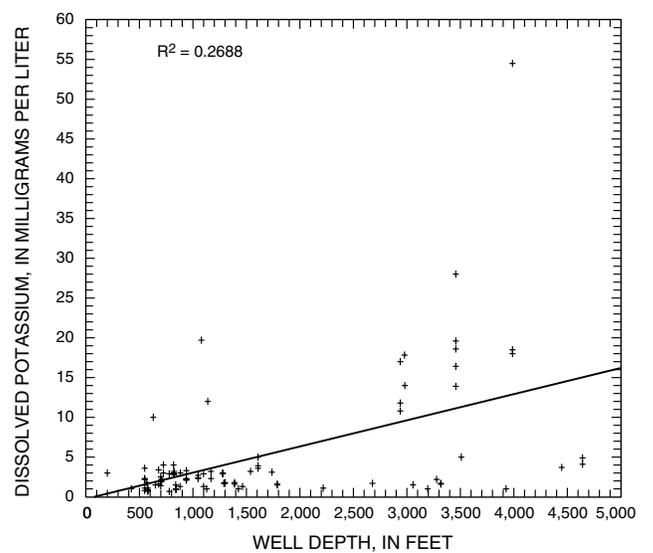
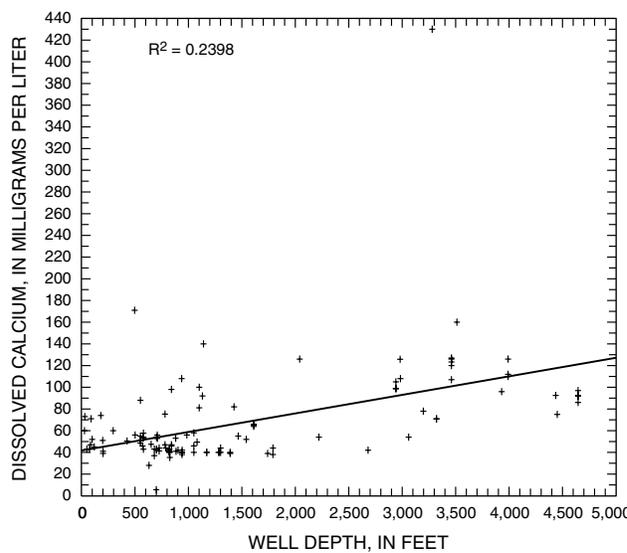
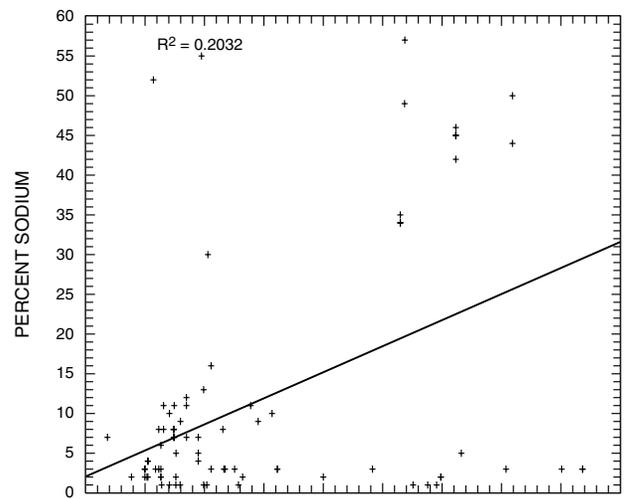
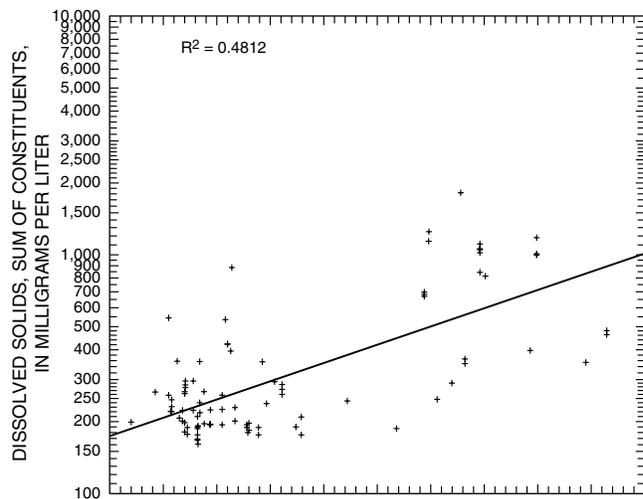
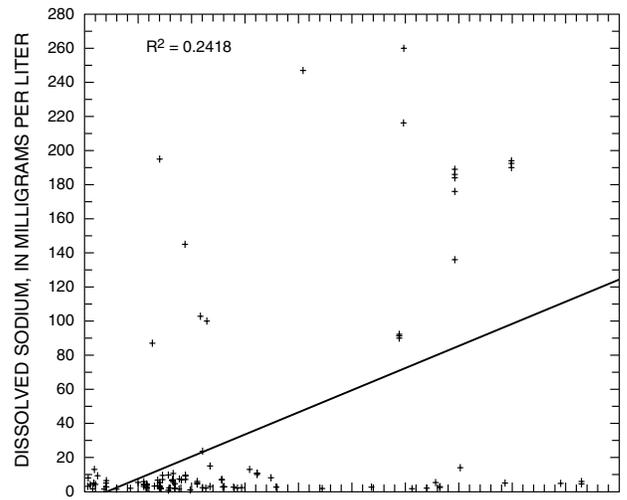
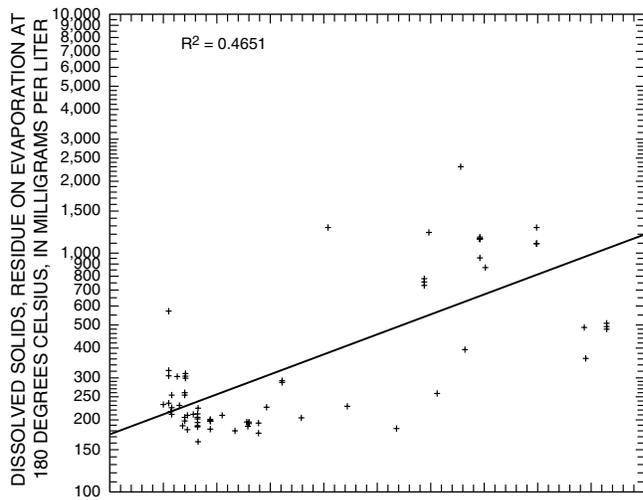


**Figure 19.** Relations between sulfate and specific conductance in the Madison, Minnelusa, and Inyan Kara aquifers.



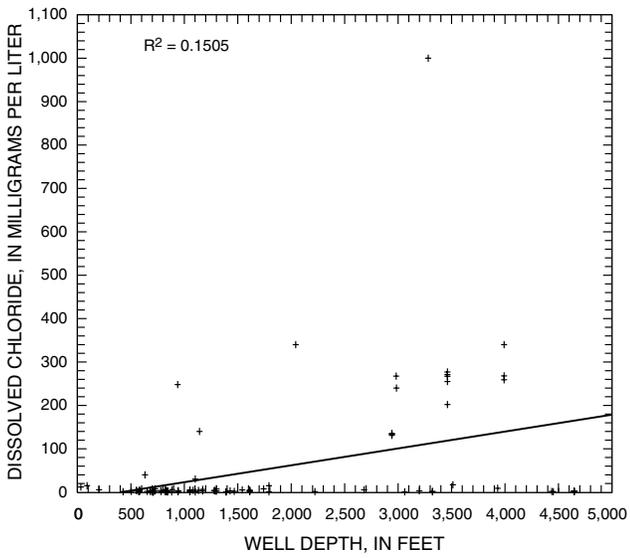
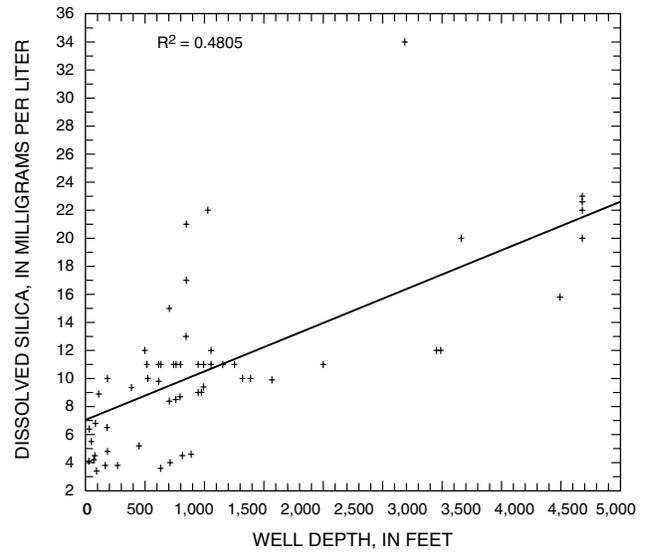
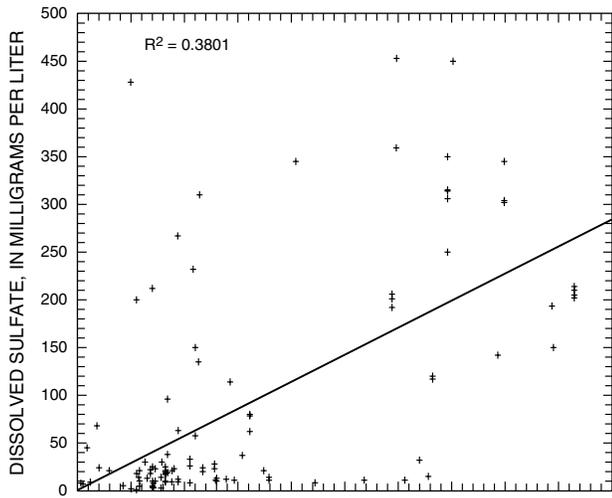
DEADWOOD AQUIFER

Figure 20. Selected relations between common ions and well depth for selected aquifers.



MADISON AQUIFER

Figure 20. Selected relations between common ions and well depth for selected aquifers.--Continued



MADISON AQUIFER

Figure 20. Selected relations between common ions and well depth for selected aquifers.--Continued

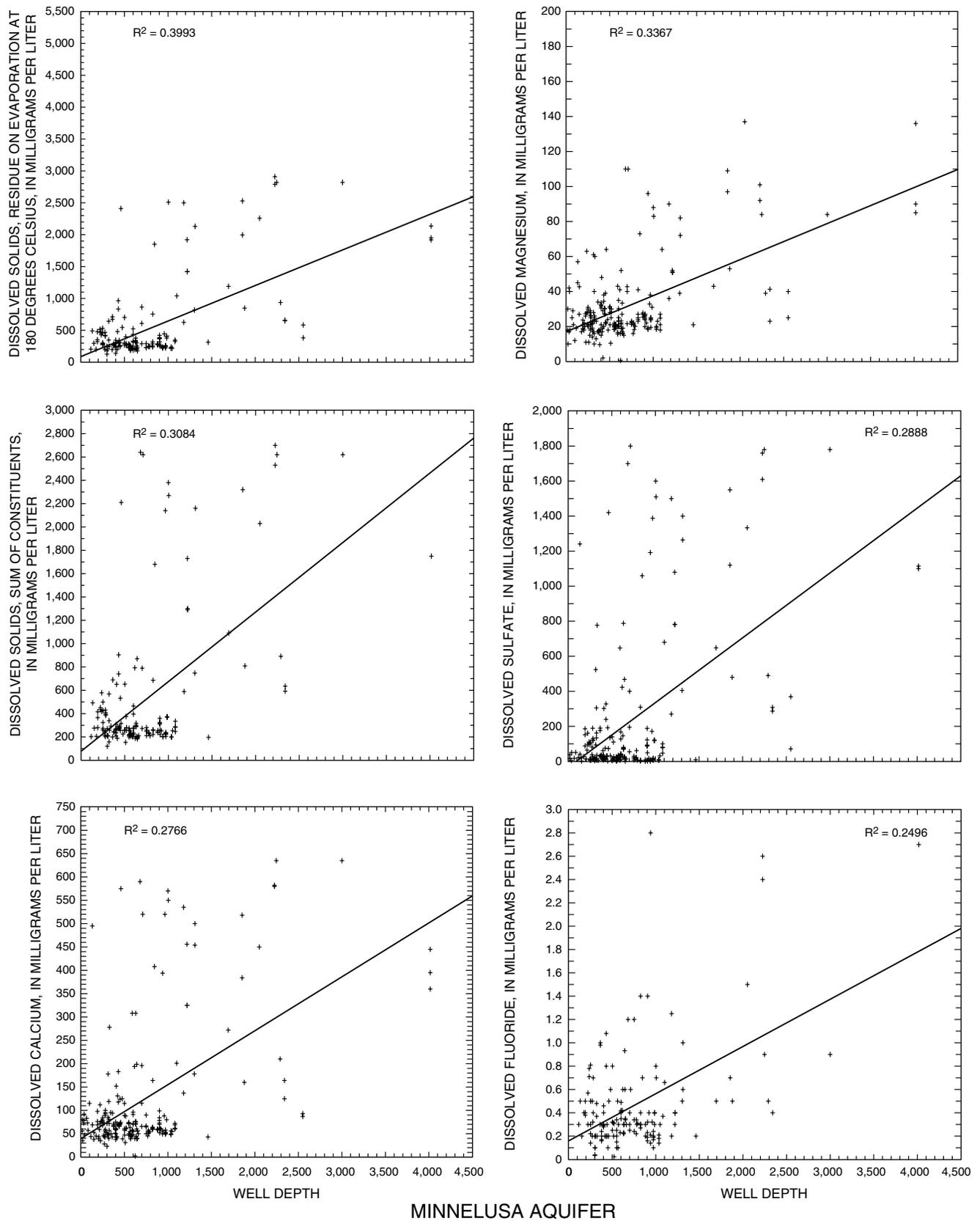
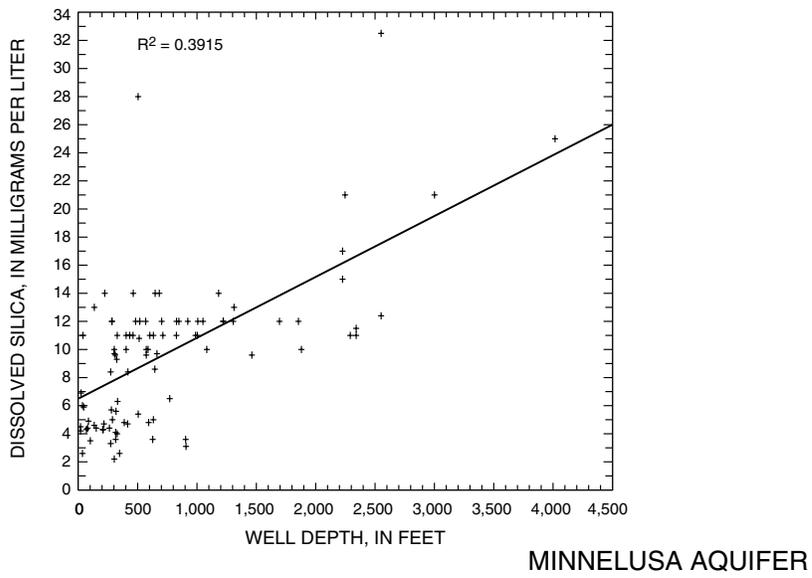
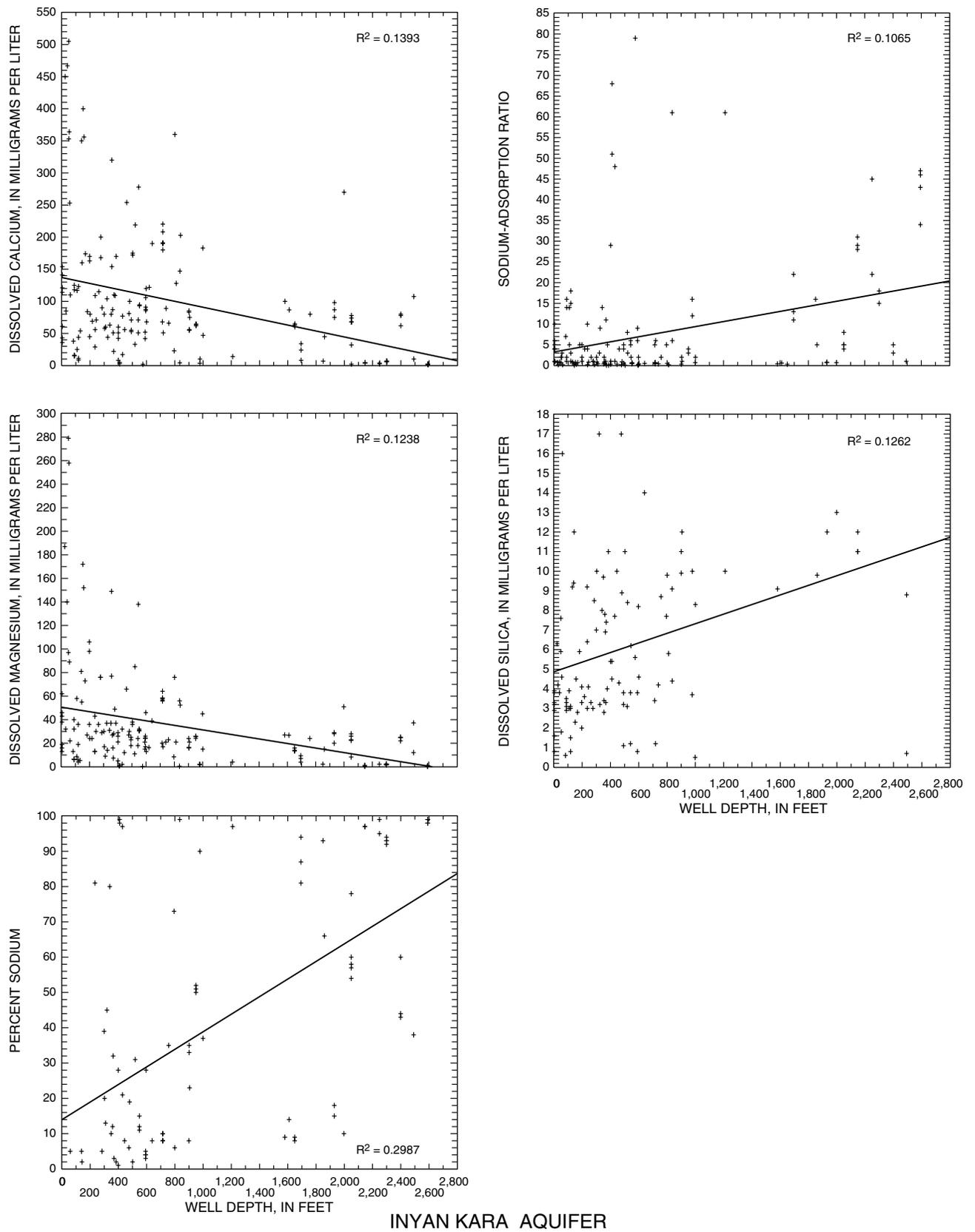


Figure 20. Selected relations between common ions and well depth for selected aquifers.--Continued





**Figure 20.** Selected relations between common ions and well depth for selected aquifers.--Continued

## Madison Aquifer

Water from the Madison aquifer generally is fresh, but can be slightly saline (dissolved solids concentration of 1,000 to 3,000 mg/L) near Edgemont, Rapid City, and northwest of Spearfish. Samples from the Madison aquifer have the highest mean chloride concentration of the major aquifers.

The two main water types in the Madison aquifer are calcium magnesium bicarbonate type and calcium sodium chloride sulfate type (fig. 17). Calcium, magnesium, and bicarbonate are dominant among the common ions throughout most of the study area due to the dissolution of calcite and dolomite. The latter water type exists only in the southwestern part of the study area (Naus and others, in press). The high concentrations of chloride, sulfate, and sodium in the southwestern part of the study area relative to the rest of the study area probably reflect the presence of more evolved ground water and regional flow from the west, and/or the presence of evaporite minerals available for dissolution (Naus and others, in press).

In the Madison aquifer, calcium, sodium, potassium, sulfate, chloride, and silica concentrations and percent sodium generally increase with increasing well depth (fig. 20). Although there were not enough values of bicarbonate concentrations with a corresponding well depth for a statistical correlation, a visual check of the well locations in relation to the outcrop showed that bicarbonate concentrations decrease with increasing distance from the outcrop and, hence, probably decrease with increasing well depth. Generally, chloride concentrations, sodium concentrations, and percent sodium are higher in Fall River County than in other counties in the study area.

About 25 percent of the samples (25 of 99) exceed the SMCL for dissolved solids (sum of constituents); all but one of these samples were collected from wells located downgradient from the outcrop with depths greater than 2,000 feet. About 16 percent of the samples (21 of 127 samples) equal or exceed the SMCL for sulfate, and about 12 percent of the samples (15 of 124 samples) equal or exceed the SMCL of 250 mg/L for chloride. All of the samples that exceed these SMCL's were collected from wells located downgradient of the outcrop and most of the wells were in Fall River County. The higher sulfate concentrations in the Madison aquifer may be caused by the dissolution of anhydrite or leakage of water from the Minnelusa aquifer (Kyllonen and Peter, 1987). One of 89 samples exceeds the MCL for fluoride.

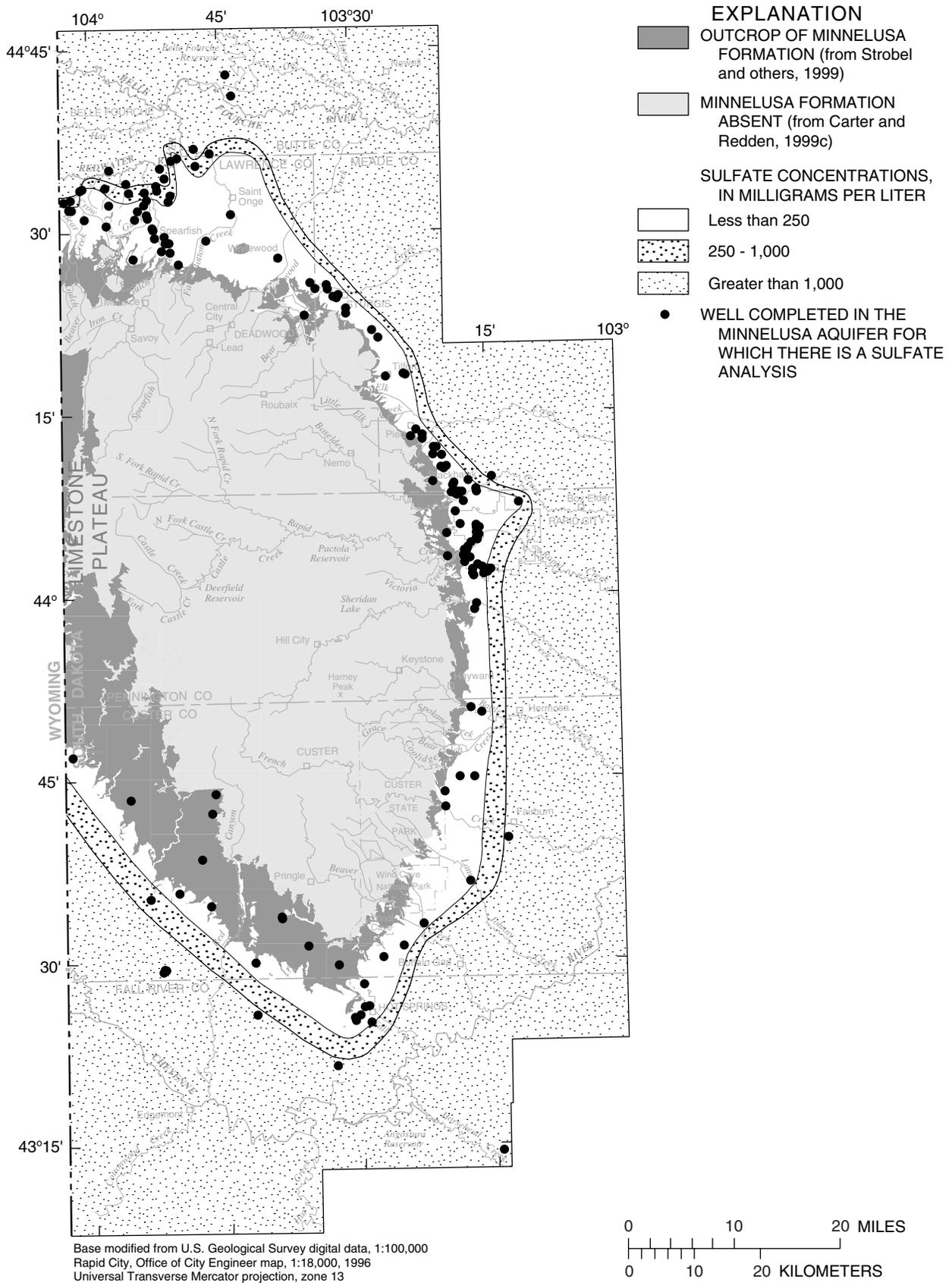
## Minnelusa Aquifer

Water from the Minnelusa aquifer typically is fresh, but can be slightly saline at some locations greater than about 5 miles from the outcrop. Generally, calcium, bicarbonate, and sulfate are dominant among the common ions in the Minnelusa aquifer. Of all the major aquifers, the Minnelusa aquifer had the highest mean calcium concentration and the lowest median sodium concentration, percent sodium (equal to samples from the Minnekahta aquifer), and SAR (equal to samples from the Minnekahta aquifer).

The three main water types in the Minnelusa Formation are calcium magnesium bicarbonate type, calcium magnesium sulfate type, and calcium magnesium bicarbonate sulfate chloride type. Water in the Minnelusa aquifer generally evolves downgradient from a calcium magnesium bicarbonate type to a calcium magnesium sulfate type due to dissolution of anhydrite. In the southern part of the study area, ground water is characterized by higher concentrations of sodium and chloride. The higher chloride concentrations in this area could reflect hydraulic connection between the Madison and Minnelusa aquifers (Naus and others, in press). The dissolution of evaporite minerals and the presence of more evolved ground water also may contribute toward the occurrence of this water type in the Minnelusa aquifer (Naus and others, in press).

In the Minnelusa aquifer, calcium, magnesium, sulfate, fluoride, and silica concentrations generally increase with increasing well depth (fig. 20). The increasing concentrations reflect the dissolution of many minerals as the water flows downgradient from the outcrop of the Minnelusa Formation. Concentrations of chloride and sodium vary with geographic location and do not show a relation to well depth (or distance from outcrop). The chloride and sodium concentrations are higher in the southern Black Hills than in other areas.

The concentration of sulfate in the aquifer is dependent on the amount of anhydrite present in the Minnelusa Formation. Near the outcrop, anhydrite has been dissolved and removed; hence, sulfate concentrations near the outcrop are low (less than 250 mg/L). Surrounding the core of the Black Hills and downgradient from the Minnelusa Formation outcrop is a sulfate transition zone (Kyllonen and Peter, 1987), within which the sulfate concentrations range from 250 to 1,000 mg/L. The transition zone is approximately 2 to 10 miles wide (fig. 21) and marks an area of active



**Figure 21.** Distribution of sulfate concentrations in the Minnelusa aquifer (from Naus and others, in press).

removal of anhydrite by dissolution. The transition zone probably is shifting downgradient over geologic time as the anhydrite in the formation is dissolved (Kyllonen and Peter, 1987). Downgradient from the transition zone, sulfate concentrations are greater than 1,000 mg/L, which represents a zone in which thick anhydrite beds remain in the formation.

More than 20 percent of the samples (38 of 176) exceed the SMCL for dissolved solids (sum of constituents); most of these samples were collected from wells located downgradient from the outcrop with depths greater than 1,000 feet. About 20 percent of the samples (51 of 249) collected exceed the SMCL for sulfate; generally most of these samples are from wells located downgradient from the outcrop. Seven of 185 samples equal or exceed the SMCL for fluoride; all 7 of these samples were located downgradient from the outcrop. None of the samples exceed the MCL for fluoride.

#### **Minnekahta Aquifer**

Water from the Minnekahta aquifer generally is fresh. Generally, calcium and bicarbonate are dominant among the common ions, although a few samples also had high sulfate concentrations. Of the major aquifers, the Minnekahta aquifer had the highest median calcium and magnesium concentrations and the highest mean and median bicarbonate and silica concentrations (table 4). The Minnekahta aquifer also had the lowest mean sodium concentration and the lowest mean and median potassium concentration, percent sodium (equal to the median of the Minnelusa aquifer), and SAR (equal to the median of the Minnelusa aquifer).

The Minnekahta aquifer generally yields a calcium bicarbonate water (fig. 17) due to the dissolution of calcite. In samples from four wells completed in the Minnekahta aquifer, the water type is calcium sulfate. The four wells with a substantial sulfate component generally are farther from the outcrop than the wells dominated by bicarbonate. A possible source for the sulfate is leakage from or through the underlying Minnelusa aquifer.

Four of 24 samples exceed the SMCL for dissolved solids (sum of constituents). Four of 28 samples exceed the SMCL for sulfate; all of these samples were collected from wells that are farther from the outcrop than the other wells that were sampled.

#### **Inyan Kara Aquifer**

Water from the Inyan Kara aquifer is fresh to slightly saline, with the highest salinity occurring in the southern Black Hills. Generally, sodium and sulfate are dominant among the common ions, although calcium and bicarbonate concentrations also can be high depending on well depth and geographic location. Of the major aquifers, the Inyan Kara aquifer had the highest mean and median sodium concentration, percent sodium, SAR, and sulfate concentration and the highest mean magnesium concentration (table 4). The Inyan Kara aquifer also had the lowest mean and median silica concentration.

The Inyan Kara aquifer may yield a sodium sulfate, calcium sulfate, calcium bicarbonate, or sodium bicarbonate water type (fig. 17) depending on geographical location and distance from the outcrop. The initial water types are similar to those of the Minnelusa aquifer—calcium sulfate or calcium bicarbonate—possibly because the Inyan Kara aquifer receives recharge from the underlying aquifers. Wells located on and near the outcrop of the Inyan Kara Group in the southern Black Hills generally yield a calcium sulfate water type, whereas wells in the eastern and northern Black Hills generally yield a calcium bicarbonate water type. In the southern Black Hills, the water evolves as it moves downgradient to a sodium sulfate water type or, locally, to a sodium bicarbonate water type (Gott and others, 1974). In the eastern and northern Black Hills, the water evolves to a sodium sulfate water type as it moves downgradient.

Percent sodium, SAR, and silica concentrations generally increase with increasing well depth, whereas calcium and magnesium concentrations decrease with increasing well depth. The change in concentrations indicates that sodium and silica are dissolving and calcium and magnesium are precipitating as the water flows downgradient from the outcrop of the Inyan Kara Group. The source of high sulfate concentrations on or near the outcrop may be from upward leakage of water from the Minnelusa aquifer or gypsiferous formations (Gypsum Spring or Spearfish Formations) or from the oxidation of sulfide minerals in the Inyan Kara aquifer (Kyllonen and Peter, 1987).

Chloride concentrations vary with geographic location as opposed to distance from outcrop. In the southern Black Hills, chloride concentrations generally are higher than those in other areas. Sulfate concentrations generally are higher in the southern Black Hills than those in other areas, whereas silica concentrations generally are lower in the southern Black Hills.

More than 60 percent of the samples (65 of 102 samples) analyzed for dissolved solids (sum of constituents) exceed the SMCL for dissolved solids; most of these samples were collected from wells in the southern Black Hills or from wells located downgradient from the outcrop with depths greater than 500 feet. More than 60 percent of the samples (110 of 177 samples) collected exceed the SMCL for sulfate; almost every sample collected in the southern Black Hills exceeds the SMCL for sulfate. Two of 105 samples equal or exceed the SMCL for fluoride, and one of these samples equals the MCL for fluoride.

### Minor Aquifers

Only three samples were analyzed for dissolved solids from the Spearfish aquifer. However, at least 25 percent of the total number of samples probably would exceed the SMCL for dissolved solids, based on sulfate concentrations that are greater than 500 mg/L. Calcium, sulfate, and bicarbonate are dominant among the common ions in the Spearfish aquifer. About 45 percent of the samples (6 of 13 samples) exceed the SMCL for sulfate. Water from the Spearfish aquifer generally is a calcium bicarbonate or calcium sulfate type (fig. 17). The dominance of sulfate increases with the amount of gypsum present in the formation.

Most samples (10 of 12 samples) from wells completed in the Sundance aquifer and some samples (3 of 7 samples) from wells completed in the Morrison aquifer exceed the SMCL for dissolved solids. In the Sundance aquifer, calcium, sodium, sulfate, and bicarbonate are dominant among the common ions. Almost all of the samples from the Sundance aquifer (12 of 14 samples) exceed the SMCL for sulfate, and 1 of 12 samples exceeds the MCL for fluoride. Most samples from the Sundance aquifer are slightly saline. Calcium, sulfate, and bicarbonate are dominant among the common ions in the Morrison aquifer. About 45 percent of the samples (7 of 15 samples) exceed the SMCL for sulfate in water from the Morrison aquifer.

No samples from the Pierre aquifer were analyzed for dissolved solids; however, it is likely that most would exceed the SMCL for dissolved solids, based on sulfate concentrations. Sodium, calcium, sulfate, and bicarbonate (based on alkalinity) are dominant among the common ions in the Pierre aquifer. The mean bicarbonate concentration is about 360 mg/L and was determined by dividing the mean alkalinity (table 3) by 0.8202 (Hem, 1985). Almost all of the

samples (24 of 28 samples) exceed the SMCL for sulfate.

Water from the Sundance, Morrison, and Pierre aquifers generally is a mixed type that includes dominant cations of sodium, calcium, and magnesium, and the dominant anions of sulfate and bicarbonate (fig. 17). The dominance of sodium and sulfate increases with increasing amounts of shale present in the formations due to the large cation-exchange capacities of clay minerals (generally sodium concentrations increase) and due to the reduced circulation of water through the shale (Hem, 1985). The dominance of calcium, magnesium, and bicarbonate increases with increasing amounts of sandstone (where calcium carbonate commonly is the cementing material) and carbonate rocks present in the formations.

No samples from aquifers in the Graneros Group (excluding the Newcastle aquifer) were analyzed for dissolved solids; however, at least 25 percent of the samples probably would exceed the SMCL for dissolved solids, based on sulfate concentrations. Wells completed in the Newcastle aquifer generally yield water that is low in specific conductance and dissolved solids, although one of eight samples from the Newcastle aquifer did exceed the SMCL for dissolved solids. Calcium, bicarbonate (based on alkalinity), and sulfate are the dominant common ions in the Graneros aquifer. Calcium and bicarbonate (based on alkalinity) are the dominant common ions in the Newcastle aquifer. None of the samples for either the Graneros or Newcastle aquifers were analyzed for bicarbonate. The mean bicarbonate concentration of the samples for both aquifers is about 300 mg/L based on the mean alkalinity (table 3). Fifty percent of the samples (5 of 10 samples) collected from the Graneros aquifer exceed the SMCL for sulfate, and one of eight samples collected from the Newcastle aquifer exceeds the SMCL for sulfate. Of the minor aquifers, the Newcastle aquifer generally has the lowest sulfate concentrations and has the lowest dissolved solids concentrations.

The water type yielded from the Graneros aquifer varies from a calcium bicarbonate sulfate type to a mixed type (fig. 17), depending on the formation in which the well is completed. Most wells completed within the Graneros Group are completed in the Newcastle aquifer, which generally yields a calcium bicarbonate or calcium bicarbonate sulfate water type.

Generally, calcium, sulfate, and bicarbonate are dominant among the common ions in the alluvial aquifers. The concentrations of all of the common ions

increase with distance from the central core of the Black Hills, which is largely due to the increasing dissolved ions in the streams and in the geologic formations that underlie the alluvial deposits. About 25 percent of the samples (20 of 81 samples) exceed the SMCL for dissolved solids (sum of constituents); almost all those samples are from wells completed in alluvial deposits that overlie the Cretaceous-age shales. More than 30 percent of the samples (38 of 116 samples) from alluvial aquifers exceed the SMCL for sulfate, and most of these are from wells completed in alluvial deposits that overlie the Cretaceous-age shales.

The water type yielded from wells completed in alluvial aquifers varies greatly (fig. 17) and largely is dependent on the geologic formation that underlies the alluvial deposit. Generally, wells completed in alluvial deposits that do not overlie Cretaceous-age shales yield fresh water with a calcium bicarbonate or calcium magnesium bicarbonate water type. Wells that are completed in alluvial deposits that overlie the Cretaceous-age shales generally yield slightly saline water with a mixed water type or a water type in which sodium is the dominant cation and/or sulfate is the dominant anion.

## Nutrients

Nitrogen and phosphorus are essential nutrients for plant growth. The major form of nitrogen in ground water is nitrate, although it also can occur in other forms including ammonium, ammonia, nitrite, and as part of organic solutes. Nitrate is very mobile in ground water, and it moves with little or no retardation (Freeze and Cherry, 1979). Elevated nitrate concentrations in ground water can originate from natural processes or as contamination from nitrogen sources, such as fertilizers and sewage. Nitrate concentrations above 10 mg/L (U.S. Environmental Protection Agency, 1994a) can cause methemoglobinemia (blue-baby syndrome) in small children.

In ground water, phosphorus generally occurs as phosphate. Orthophosphate generally is the most stable phosphate species that occurs. Phosphorus has a low solubility and, therefore, dissolved concentrations in ground water generally are no more than a few tenths of a milligram per liter (Hem, 1985). Concentrations above this level may indicate contamination by

fertilizer or sewage. Concentrations of orthophosphate that were reported as phosphate were converted to concentrations as phosphorus for this report.

Summary statistics for selected nutrients, including nitrite, nitrite plus nitrate, ammonia, ammonia plus organic, phosphorus, and orthophosphate, are presented in table 6, and the significance of the various nutrients is described in table 1. Boxplots are presented in figure 22 for each of the nutrients.

Generally, concentrations of nitrogen and phosphorus are low in water from the major aquifers. Two of 40 samples collected from wells completed in Precambrian aquifers exceed the MCL of 10 mg/L for nitrite plus nitrate. No samples from the Deadwood, Madison, or Minnekahta aquifers exceed the MCL for any regulated nutrient constituent. A sample from the Madison aquifer has the highest concentration of ammonia plus organic (5.0 mg/L) of all the samples from all of the aquifers considered in this study. In the Minnelusa aquifer, 2 of 157 samples exceed the MCL for nitrite plus nitrate. A sample from the Minnelusa aquifer has the highest phosphorus concentration (2.1 mg/L) of all the samples from all aquifers considered in this study.

Nitrogen and phosphorus concentrations generally are low in water from the Inyan Kara aquifer. Of the samples collected from wells completed in the Inyan Kara aquifer, 1 of 41 samples equalled the MCL of 1.0 mg/L for nitrite, and 1 of 81 samples exceeds the MCL for nitrite plus nitrate. Three individual samples from the Inyan Kara aquifer have the highest concentration of nitrite (1.0 mg/L), nitrite plus nitrate (60 mg/L), and ammonia (2.2 mg/L) of all the samples from all aquifers considered in this study (fig. 22). The extreme values for nitrite and nitrite plus nitrate are unusually high and may reflect poor well construction and surface contamination as opposed to aquifer conditions.

With the exception of alluvial aquifers, few samples from the minor aquifers were analyzed for nitrogen or phosphorus. Of the samples analyzed, nitrogen and phosphorus concentrations are low and none exceed the MCL for nitrite or for nitrite plus nitrate.

**Table 6.** Summary of concentrations of nutrients in ground water

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter. One milligram per liter is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Precambrian aquifers</b>						
Nitrite, as N	18	17	--	--	<0.01	0.01
Nitrite plus nitrate, as N	40	8	1.6	0.7	<0.1	12
Ammonia, as N	0	--	--	--	--	--
Ammonia plus organic, as N	0	--	--	--	--	--
Phosphorus, as P	51	44	<sup>1</sup> --	<sup>1</sup> --	<0.04	0.12
Orthophosphate, as P	0	--	--	--	--	--
<b>Deadwood aquifer</b>						
Nitrite, as N	5	5	--	--	<0.01	<0.01
Nitrite plus nitrate, as N	8	4	0.2	<0.1	<0.1	0.5
Ammonia, as N	2	0	0.025	0.025	0.02	0.03
Ammonia plus organic, as N	3	1	--	--	<0.2	0.6
Phosphorus, as P	7	5	--	--	<0.01	0.25
Orthophosphate, as P	1	1	--	--	<0.001	<0.001
<b>Madison aquifer</b>						
Nitrite, as N	56	50	<sup>1</sup> --	<sup>1</sup> --	<0.01	0.03
Nitrite plus nitrate, as N	74	14	0.4	0.2	<0.05	2.6
Ammonia, as N	31	12	0.2	0.01	<0.01	1.9
Ammonia plus organic, as N	36	23	0.4	0.1	0.05	5.0
Phosphorus, as P	59	42	0.01	<0.01	<0.01	0.22
Orthophosphate, as P	28	14	<0.01	<0.01	<0.01	0.02
<b>Minnelusa aquifer</b>						
Nitrite, as N	61	49	<sup>1</sup> --	<sup>1</sup> --	<0.01	0.05
Nitrite plus nitrate, as N	157	29	0.6	0.3	0.01	16
Ammonia, as N	22	6	0.04	0.02	<0.01	0.3
Ammonia plus organic, as N	28	16	0.2	0.2	<0.1	0.8
Phosphorus, as P	68	54	0.04	<0.01	<0.01	2.1
Orthophosphate, as P	19	11	<0.01	<0.01	<0.01	0.03
<b>Minnekahta aquifer</b>						
Nitrite, as N	10	9	--	--	<0.01	0.01
Nitrite plus nitrate, as N	23	4	1.5	0.7	<0.1	9.5
Ammonia, as N	3	1	--	--	<0.02	0.07
Ammonia plus organic, as N	3	1	--	--	<0.2	0.2
Phosphorus, as P	4	3	--	--	<0.01	<0.04
Orthophosphate, as P	3	1	--	--	<0.01	0.03

**Table 6.** Summary of concentrations of nutrients in ground water—Continued

[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter. One milligram per liter is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

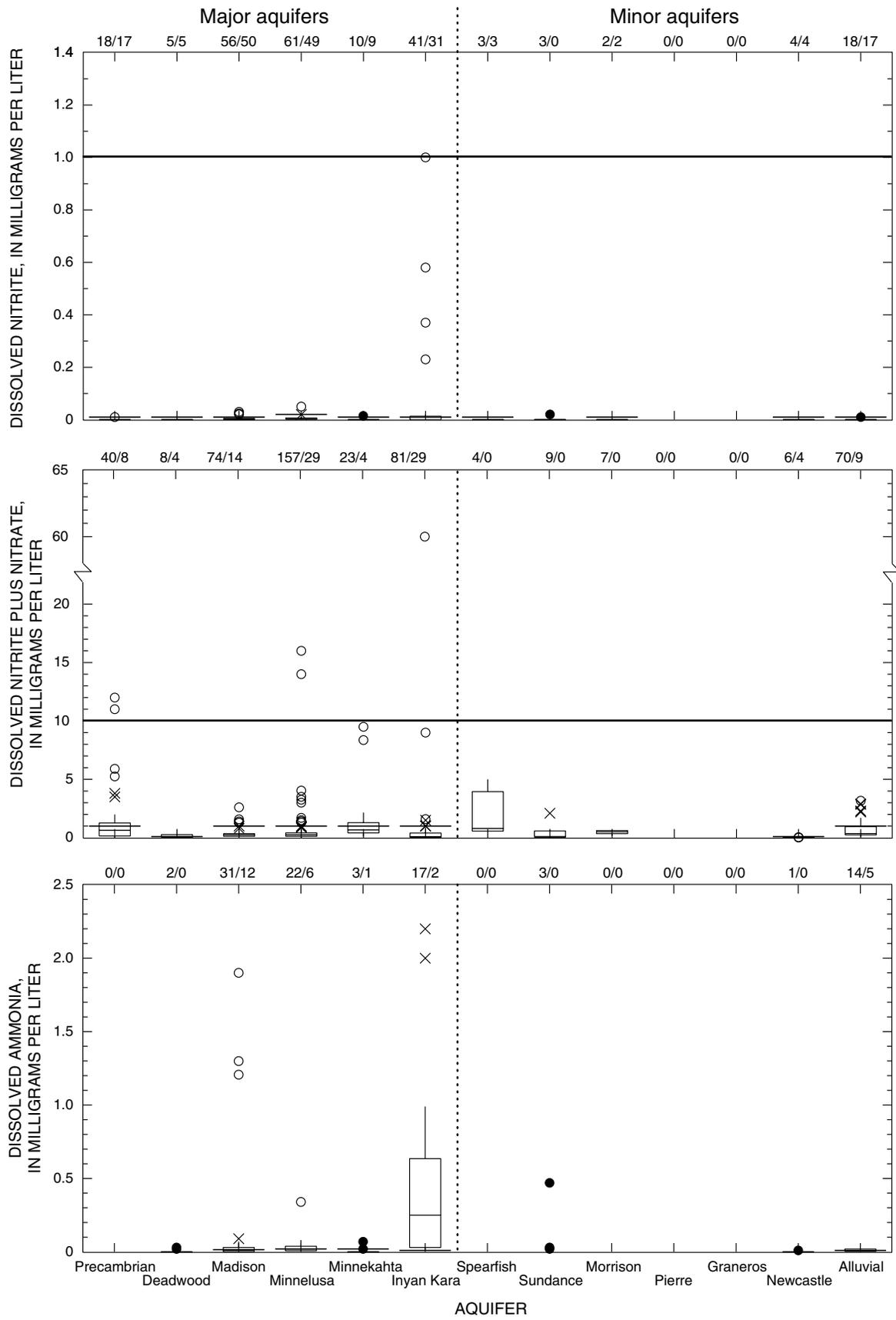
Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Inyan Kara aquifer</b>						
Nitrite, as N	41	31	0.06	<0.01	<0.01	1.0
Nitrite plus nitrate, as N	81	29	1.1	0.1	0.01	60
Ammonia, as N	17	2	0.5	0.25	<0.01	2.2
Ammonia plus organic, as N	18	1	0.8	0.5	<0.1	2.7
Phosphorus, as P	81	74	--	--	<0.01	0.03
Orthophosphate, as P	0	0	--	--	--	--
<b>Spearfish aquifer</b>						
Nitrite, as N	3	3	--	--	<0.01	<0.01
Nitrite plus nitrate, as N	4	0	1.8	0.8	0.5	5.0
Ammonia, as N	0	--	--	--	--	--
Ammonia plus organic, as N	0	--	--	--	--	--
Phosphorus, as P	9	9	--	--	<0.04	<0.04
Orthophosphate, as P	0	--	--	--	--	--
<b>Sundance aquifer</b>						
Nitrite, as N	3	0	0.02	0.02	0.02	0.02
Nitrite plus nitrate, as N	9	0	0.4	0.1	0.02	2.1
Ammonia, as N	3	0	0.2	0.03	0.02	0.5
Ammonia plus organic, as N	3	0	0.5	0.5	0.3	0.6
Phosphorus, as P	5	4	--	--	<0.01	<0.04
Orthophosphate, as P	0	--	--	--	--	--
<b>Morrison aquifer</b>						
Nitrite, as N	2	2	--	--	<0.01	<0.01
Nitrite plus nitrate, as N	7	0	0.5	0.5	0.2	0.7
Ammonia, as N	0	--	--	--	--	--
Ammonia plus organic, as N	0	--	--	--	--	--
Phosphorus, as P	6	6	--	--	<0.04	<0.04
Orthophosphate, as P	0	--	--	--	--	--
<b>Pierre aquifer</b>						
Nitrite, as N	0	--	--	--	--	--
Nitrite plus nitrate, as N	0	--	--	--	--	--
Ammonia, as N	0	--	--	--	--	--
Ammonia plus organic, as N	0	--	--	--	--	--
Phosphorus, as P	28	26	--	--	<0.04	0.10
Orthophosphate, as P	0	--	--	--	--	--

**Table 6.** Summary of concentrations of nutrients in ground water—Continued

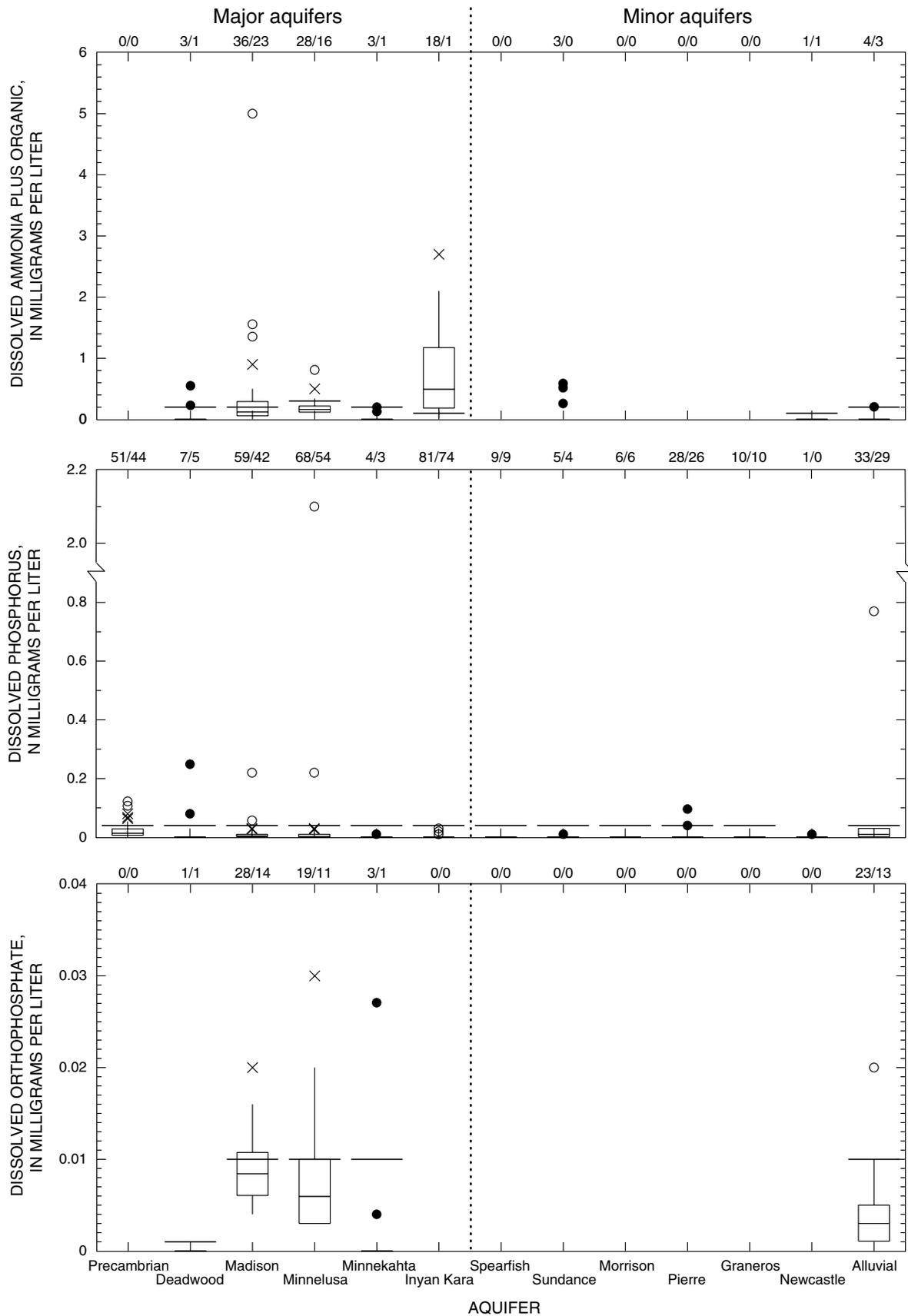
[Results based on data stored in U.S. Geological Survey National Water Information System water-quality database. Results in milligrams per liter. One milligram per liter is approximately equal to one part per million; --, not analyzed or not determined; <, less than indicated detection limit]

Dissolved constituent	Number of samples	Number of censored samples	Mean	Median	Minimum	Maximum
<b>Graneros aquifer</b>						
Nitrite, as N	0	--	--	--	--	--
Nitrite plus nitrate, as N	0	--	--	--	--	--
Ammonia, as N	0	--	--	--	--	--
Ammonia plus organic, as N	0	--	--	--	--	--
Phosphorus, as P	10	10	--	--	<0.04	<0.04
Orthophosphate, as P	0	--	--	--	--	--
<b>Newcastle aquifer</b>						
Nitrite, as N	4	4	--	--	<0.01	<0.01
Nitrite plus nitrate, as N	6	4	--	--	<0.1	<0.1
Ammonia, as N	1	0	--	--	0.01	0.01
Ammonia plus organic, as N	1	1	--	--	<0.1	<0.1
Phosphorus, as P	1	0	--	--	0.01	0.01
Orthophosphate, as P	0	--	--	--	--	--
<b>Alluvial aquifers</b>						
Nitrite, as N	18	17	--	--	<0.01	0.01
Nitrite plus nitrate, as N	70	9	0.7	0.4	0.01	3.1
Ammonia, as N	14	5	0.01	<0.01	<0.01	0.02
Ammonia plus organic, as N	4	3	--	--	<0.2	0.2
Phosphorus, as P	33	29	<sup>1</sup> --	<sup>1</sup> --	<0.01	0.77
Orthophosphate, as P	23	13	<0.01	<0.01	<0.001	0.02

<sup>1</sup>Boxplot for constituent is shown in figure 22, although percent of censored values is greater than 80 percent. Mean and median are not reported because they are unreliable.



**Figure 22.** Boxplots of concentrations of selected nutrients for selected aquifers.



**Figure 22.** Boxplots of concentrations of selected nutrients for selected aquifers.--Continued